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Title: Introduction to Radiation Effects (neutrons)

Author(s): Rech, Paolo

Intended for: present at radiation effects summer school at LANL

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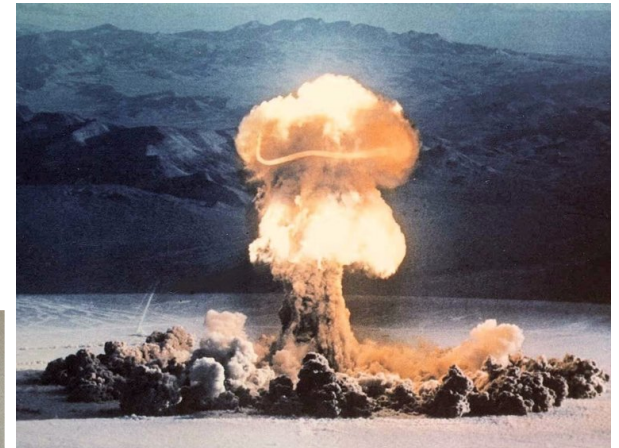
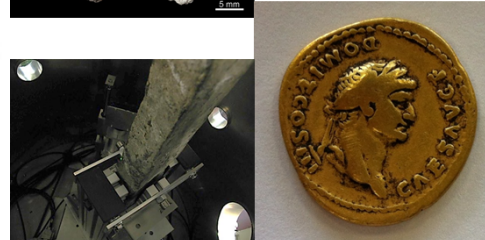
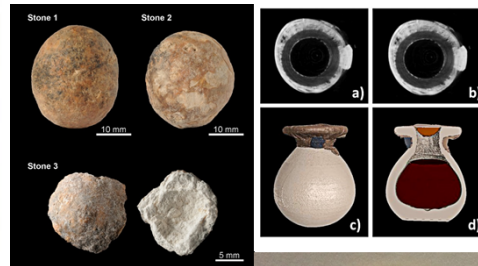
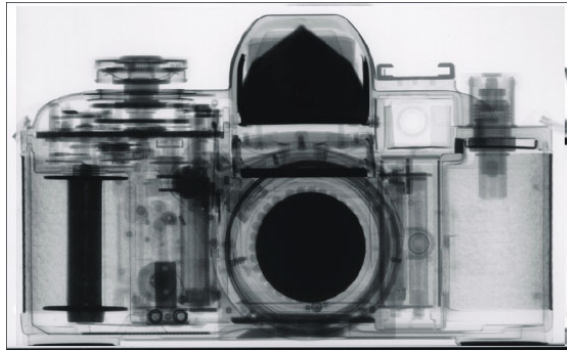
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Introduction to Radiation Effects (neutrons)

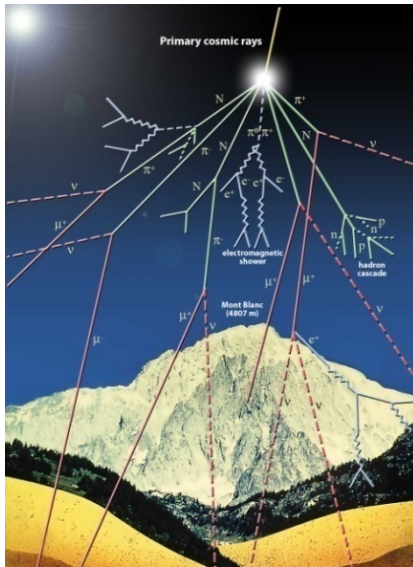
Paolo Rech



Neutrons: good or bad?



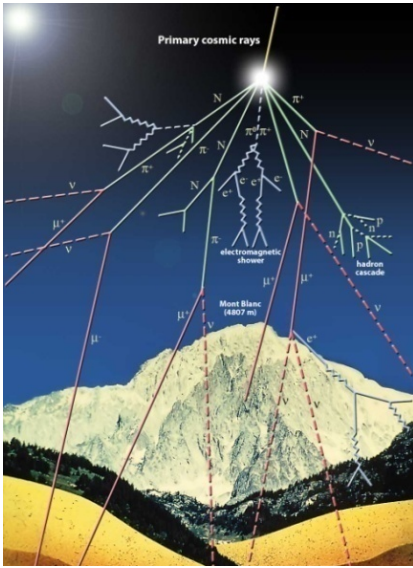
Neutrons: good or bad?



Galactic cosmic rays interacting with atmosphere generate a
shower of energetic particles:

Muons, Pions, Protons, Gamma rays,
Neutrons $\sim 13 \text{ n}/(\text{cm}^2 \cdot \text{h})$ @sea level

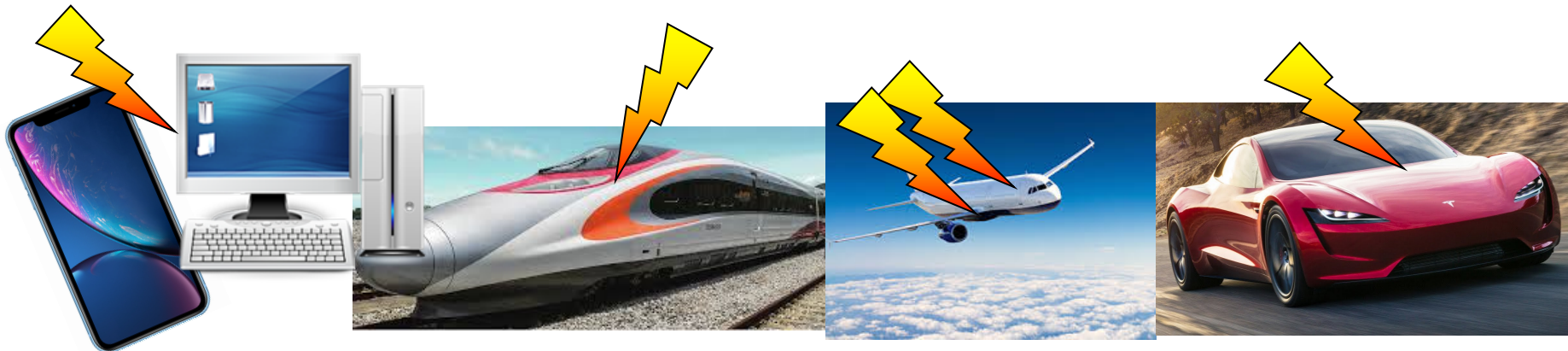
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Neutrons induce faults in modern computing systems



Space Radiation Environment

SPACE

Galactic cosmic rays

Protons
Ions



Generated by:

- Supernova explosions
- Celestial bodies collisions
- Other major events

Normally heavy elements (Ph, Au, etc..)

Wandering around the universe they
loose e^- or p^+

Interacting with planets magnetic fields
they gain energy (GeV, TeV)

Space Radiation Environment

SPACE

Galactic cosmic rays

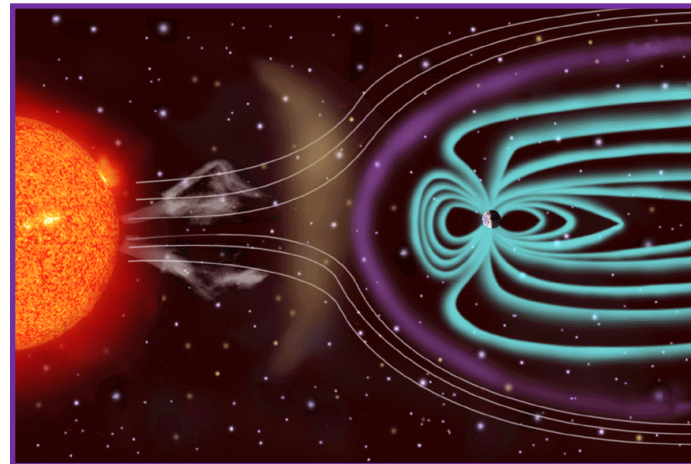
Protons
Ions

Solar wind and flares

Protons
Ions

Van Allen belts

Protons
Electrons



Space Radiation – Solar Flares

Large amount of particles release from the sun

- Once a week, when the sun “activity” is low,
- Or several times per day when the sun is very “active”

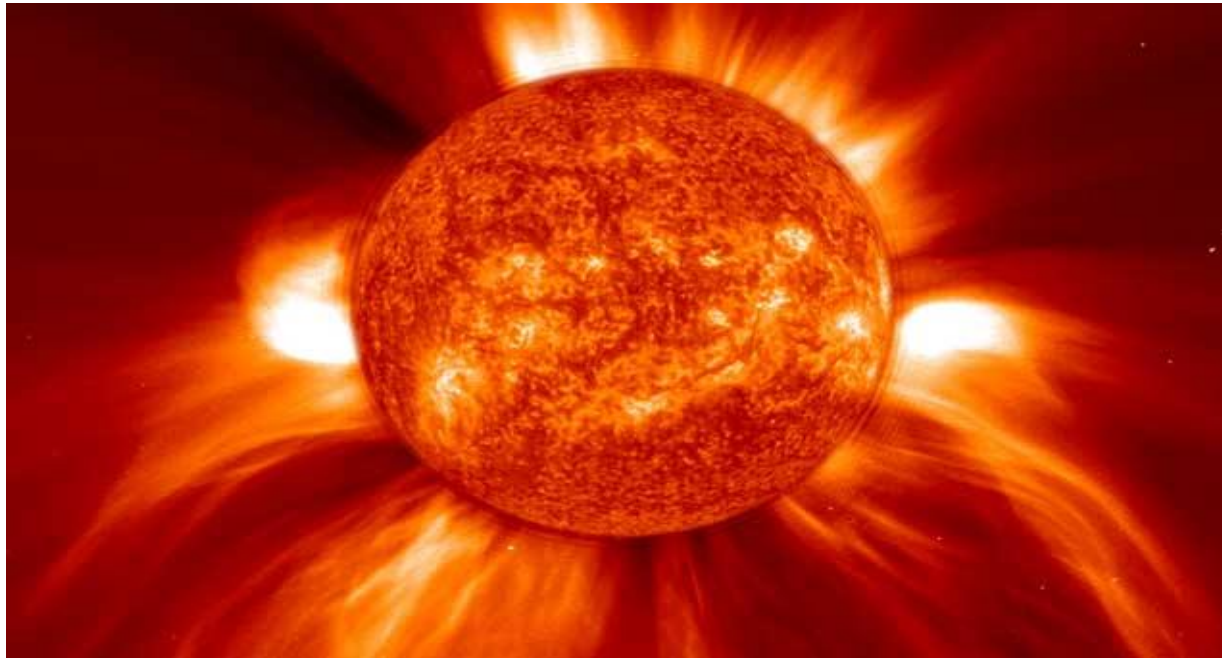


Space Radiation – Solar Wind

Continuous outward flow of particles

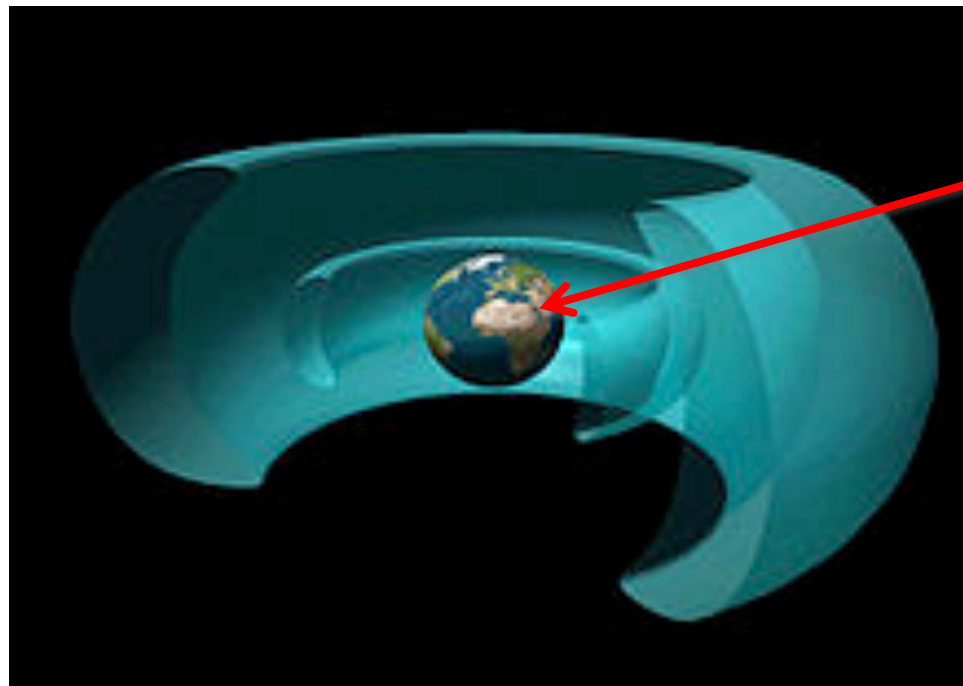
Speeds of 300 to 800 km/h

In all directions away from the sun



Space Radiation – Van Allen Belts

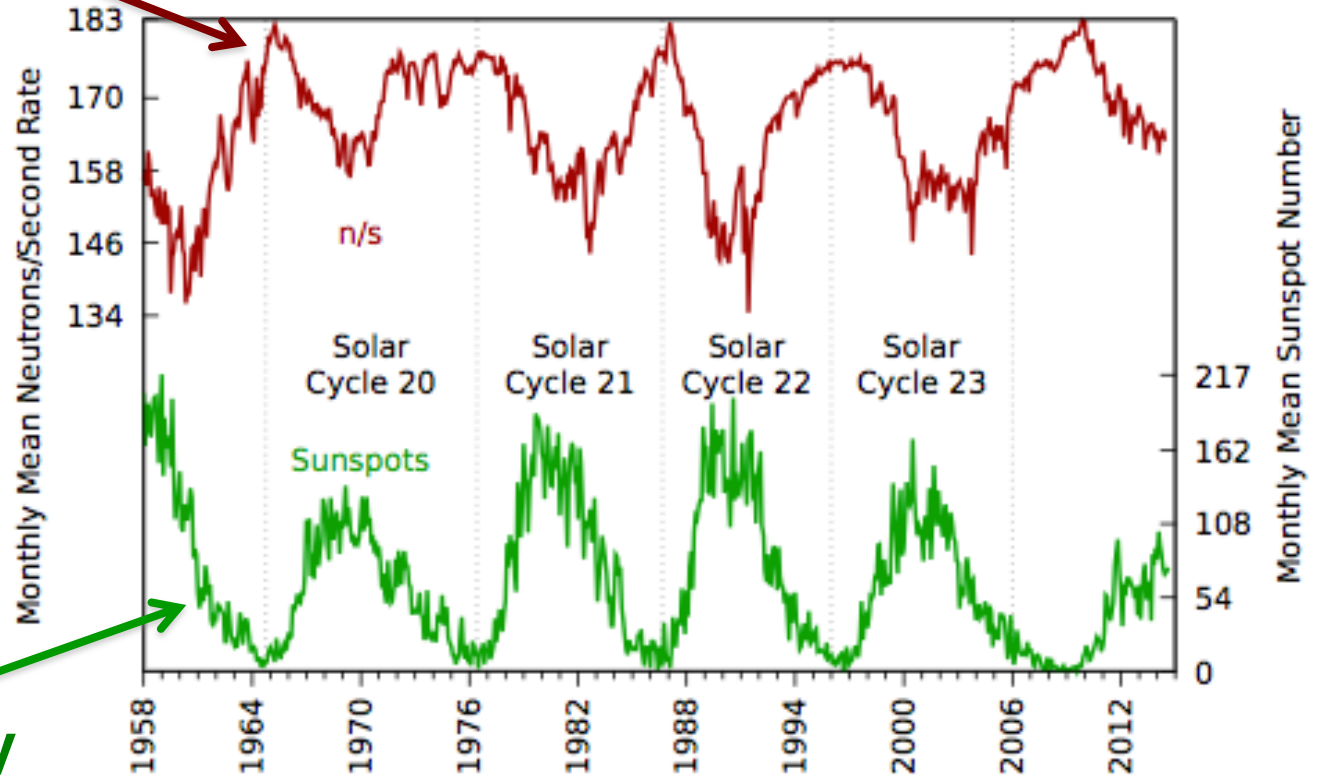
Two radiation belts surrounding Earth
Layers of energetic charged particles



Cosmic Ray

Radiation vs Solar Activity

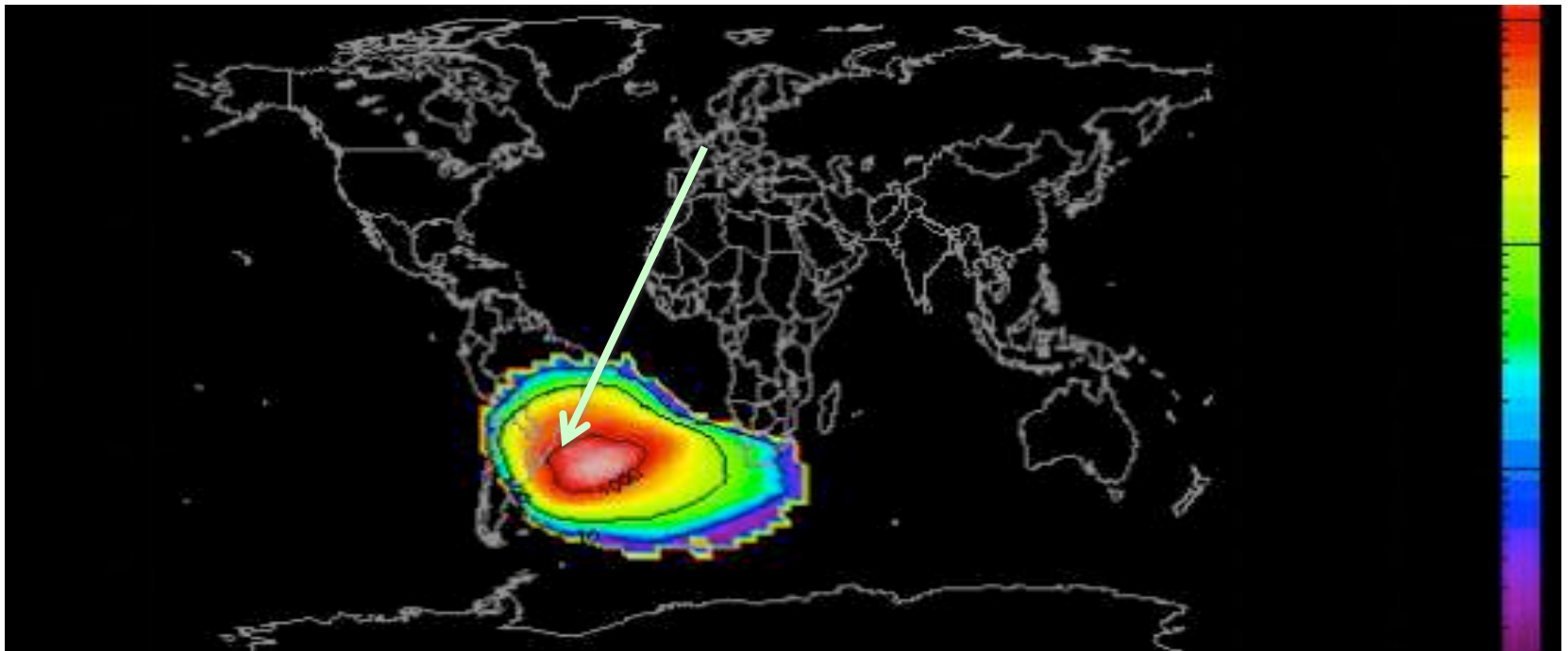
Neutron flux @ sea level



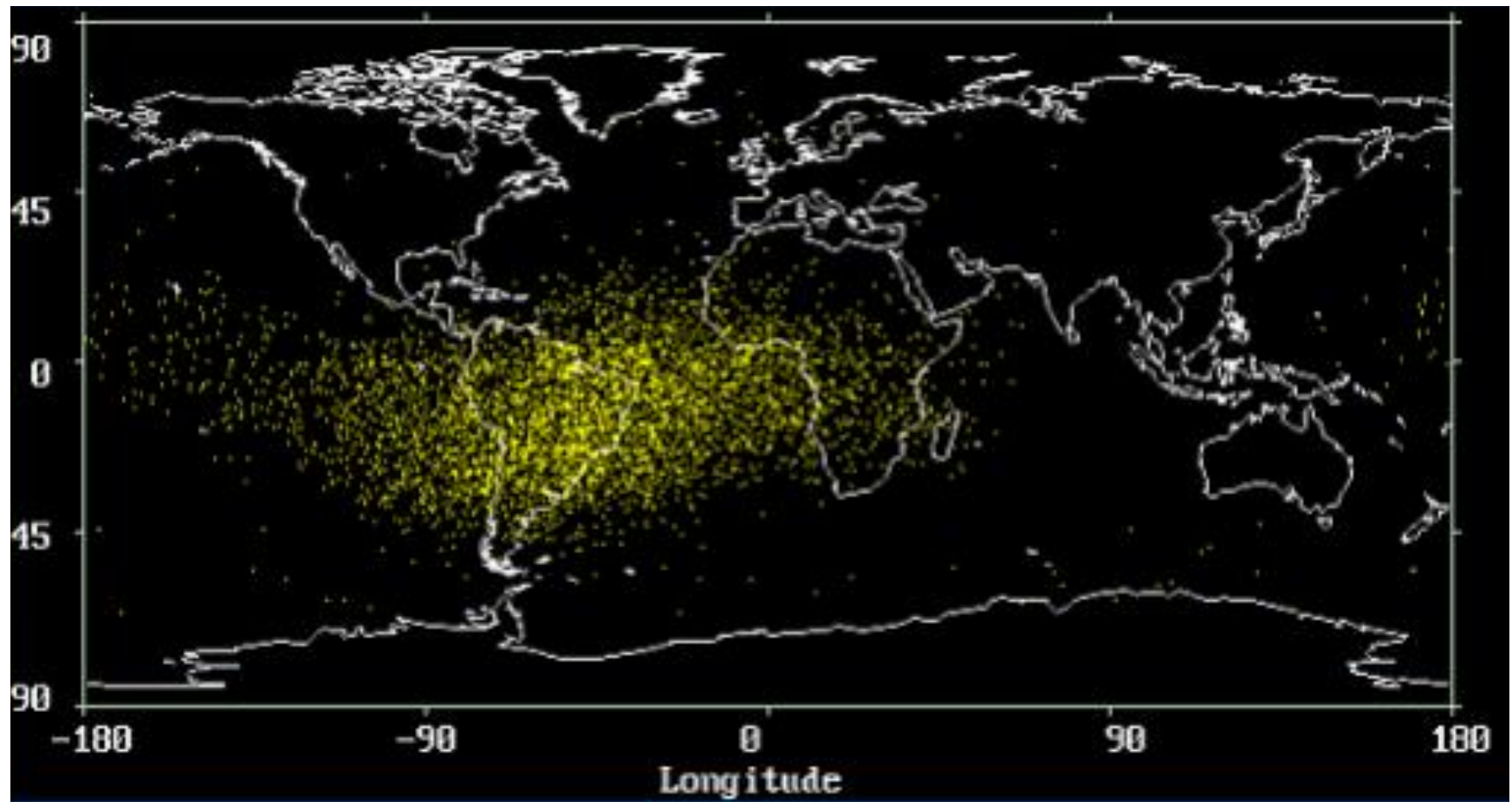
Solar Activity

South Atlantic Anomaly

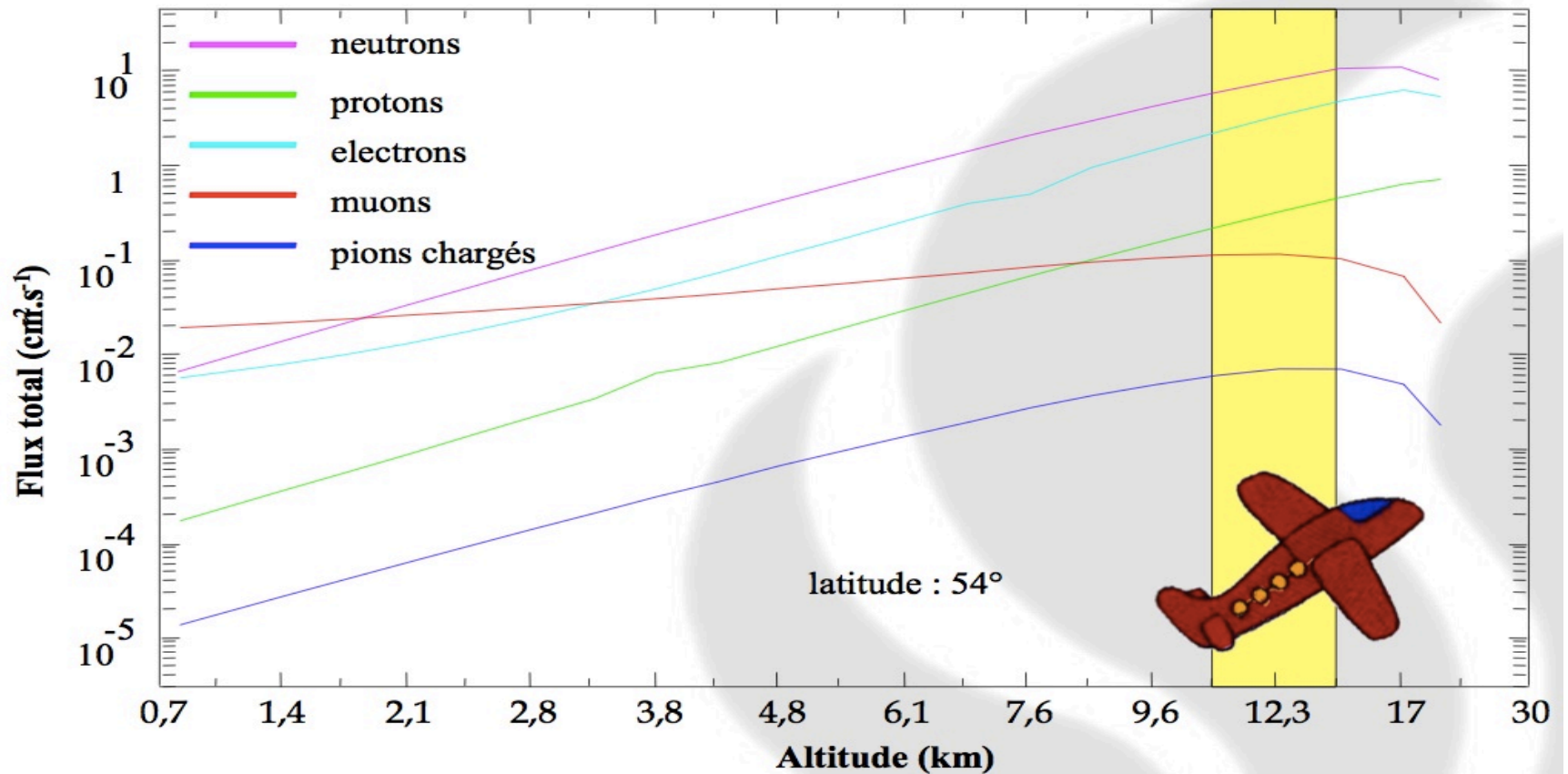
Area area where the inner Van Allen radiation belt is closer to the Earth's surface (250% higher flux)



South Atlantic Anomaly



Altitude and Radiation



Maximum ionization @ ~13KM above sea level

Terrestrial Radiation – other sources

Nuclear plants

Nuclear accidents

Certain equipment/High Energy physics experiments

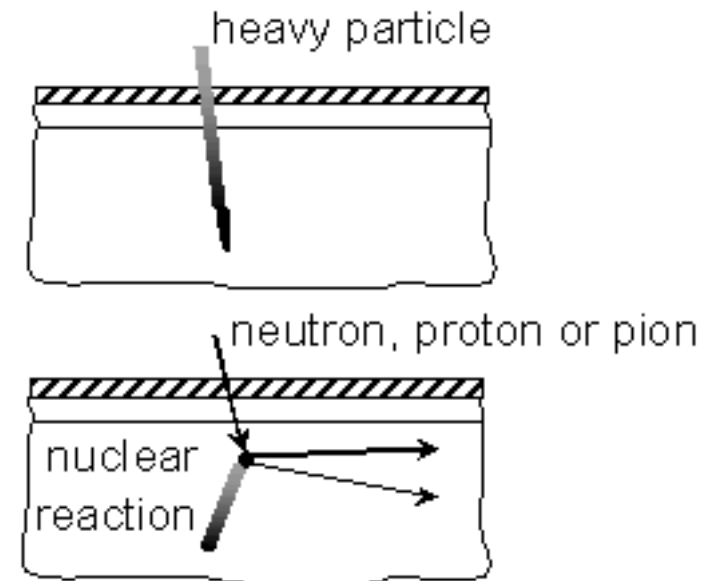
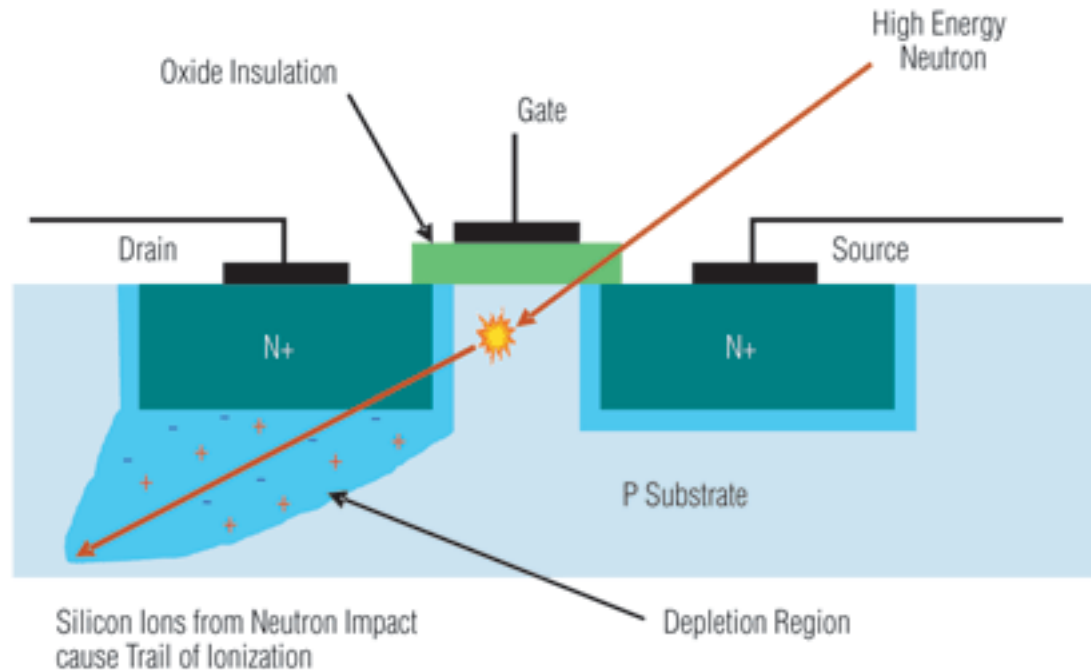
Package material (alpha particles)

....

- Why neutrons disturb computing devices
- Evaluating neutron-induced errors probabilities
- “Fun” facts about neutron-induced errors
- Some (interesting) results on self-driven cars
- What’s next?

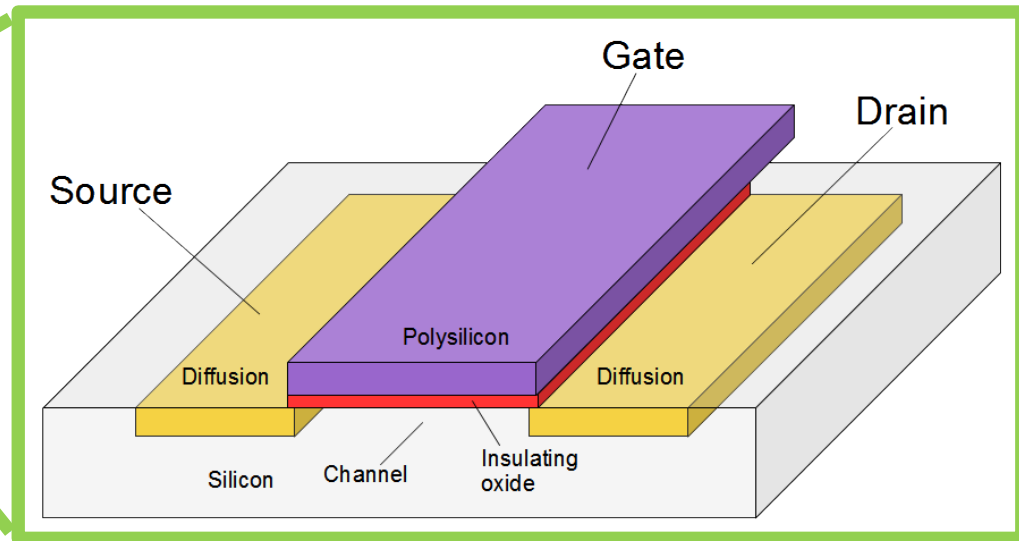
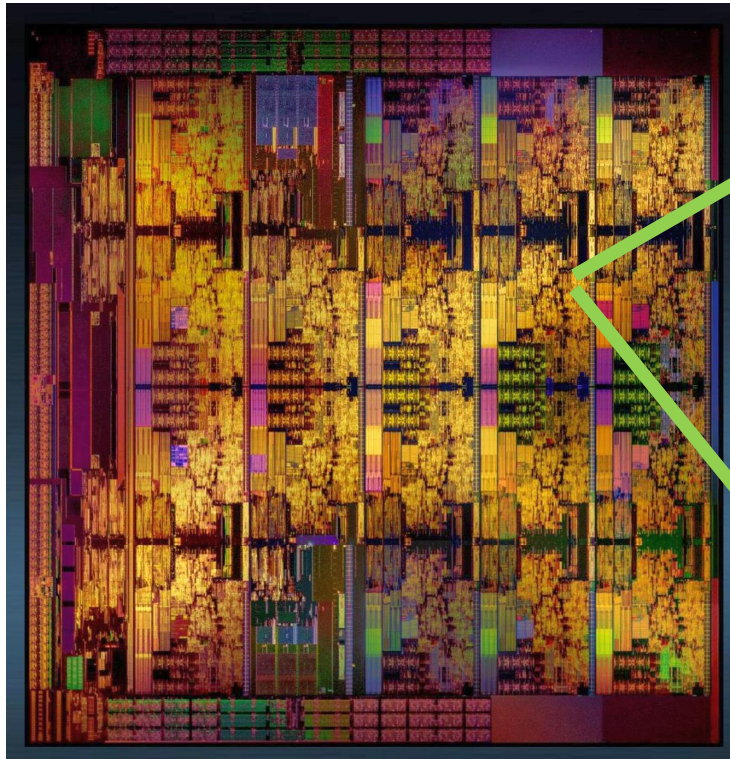
- **Why neutrons disturb computing devices**
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Radiation Effects - Neutrons



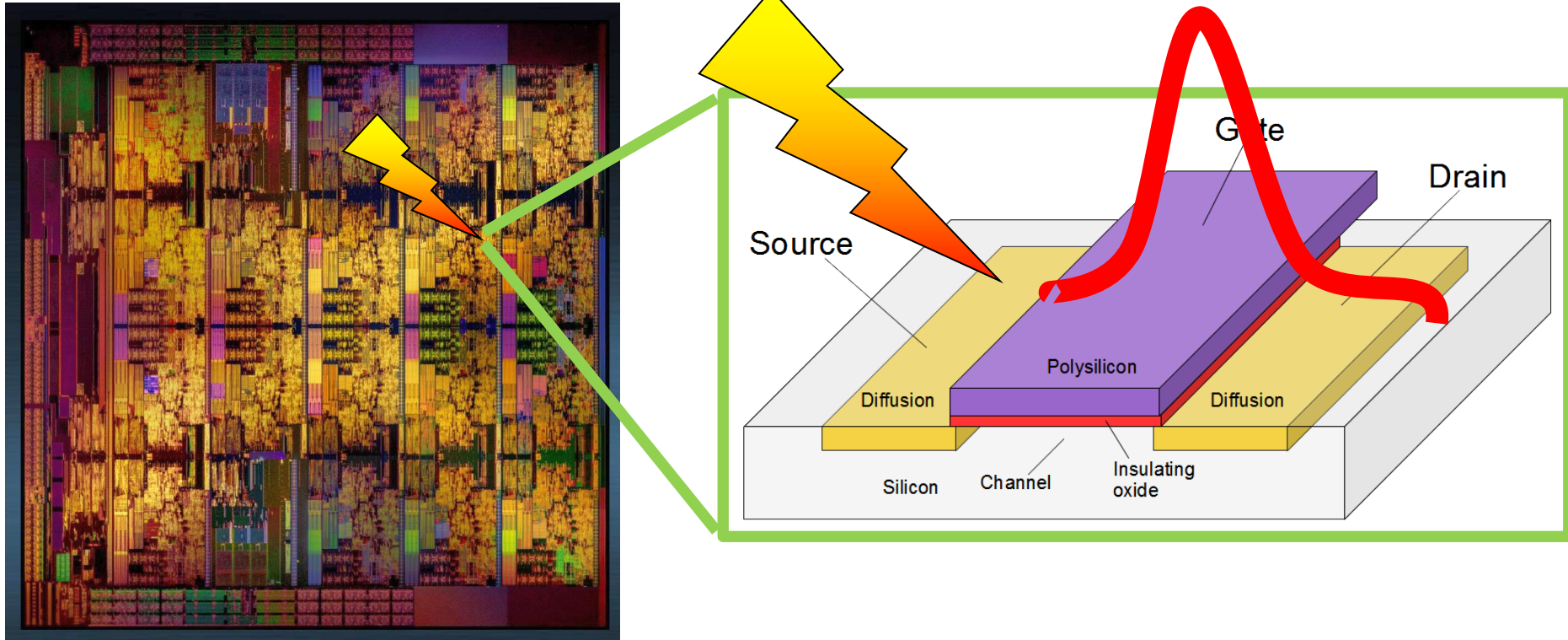
Radiation Effects - Soft Errors

Processors are composed of Billions of transistors, which are “switches” of tiny dimensions (~ 7 nm)



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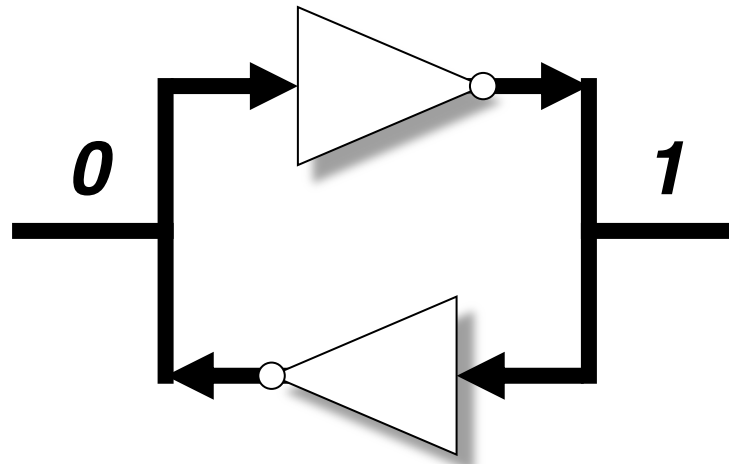
Ionizing particles (neutrons indirectly) induce current spikes that **perturb the transistor(s) state** (**OFF \rightarrow ON**)

Radiation Effects - Soft Errors

Soft Errors: the device is not permanently damaged, but the particle may generate:

- One or more bit-flips
 - Single Event Upset (SEU)
 - Multiple Bit Upset (MBU)

```
0110010010010011
1101001101001001
0010010010010010
1000100010000010
```



Radiation Effects - Soft Errors

Soft Errors: the device is not permanently damaged, but the particle may generate:

- One or more bit-flips

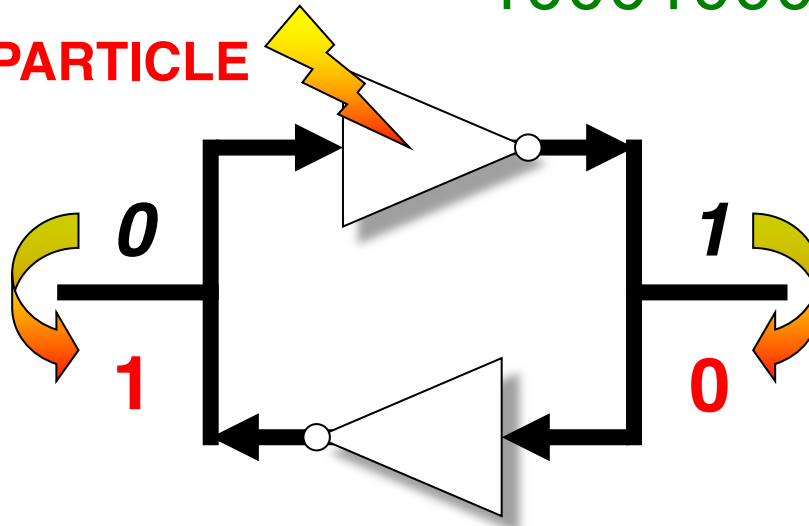
Single Event Upset (SEU)

Multiple Bit Upset (MBU)

IONIZING PARTICLE

0110010010010011
1101001011001001
0010010100010010
1000100010000010

IONIZING PARTICLE



Radiation Effects - Soft Errors

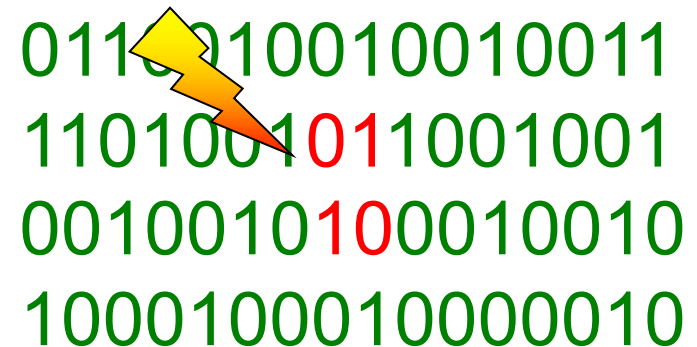
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Multiple Bit Upset (MBU)

IONIZING PARTICLE

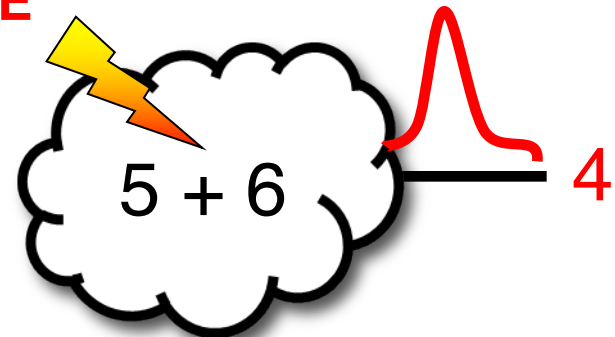


0110010010010011
1101001011001001
0010010100010010
1000100010000010

- Transient voltage pulse

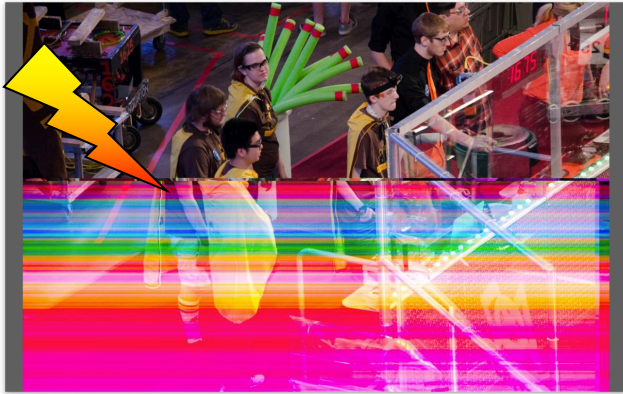
Single Event Transient (SET)

IONIZING PARTICLE



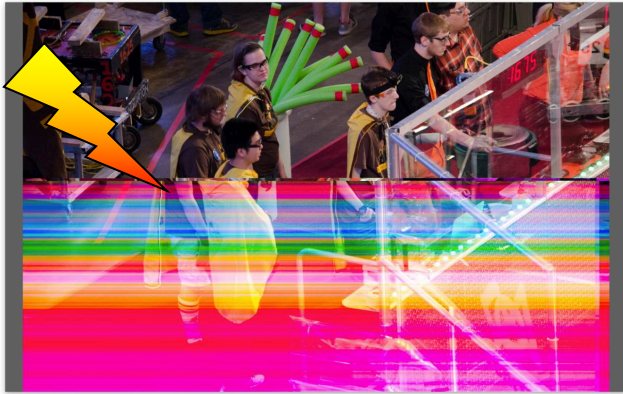
Silent Data Corruption vs Crash

Silent Data Corruption: the application provides wrong answers. **Silent** = no flag/no indication of error.



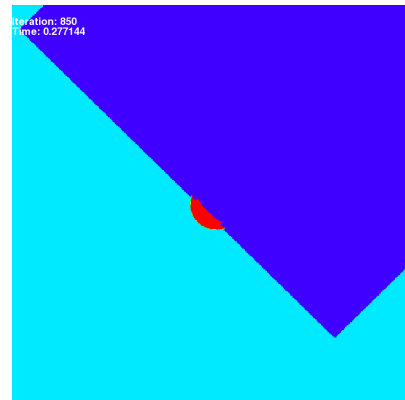
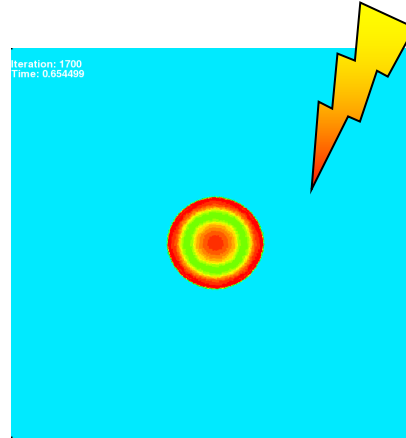
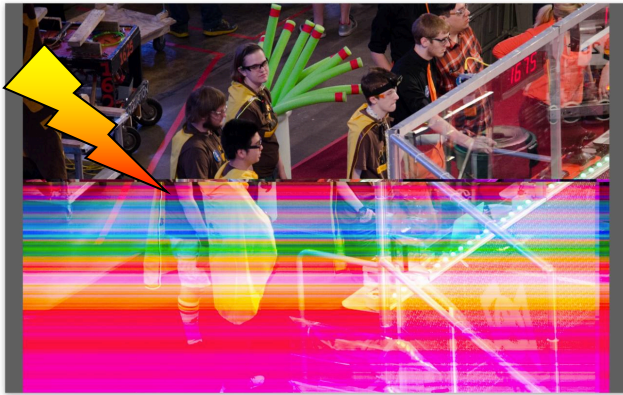
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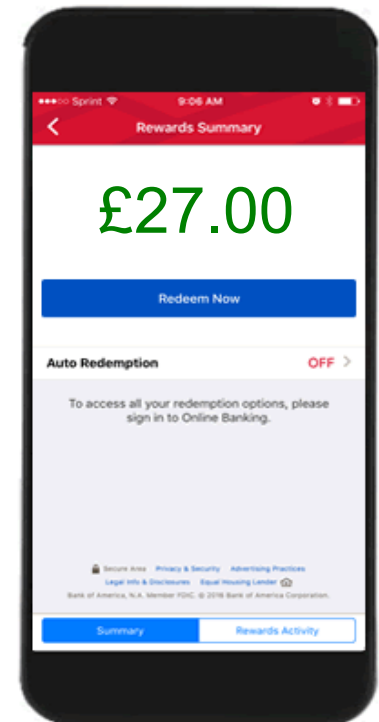
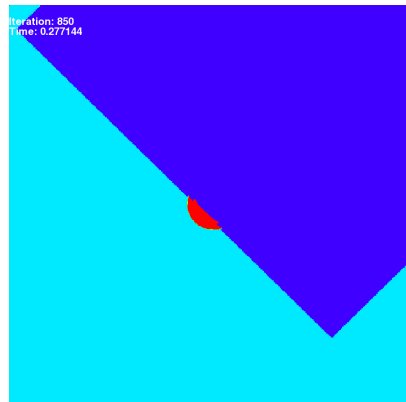
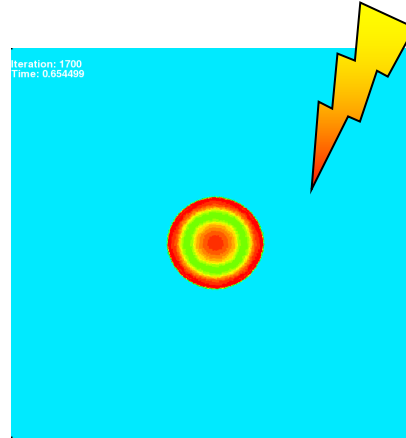
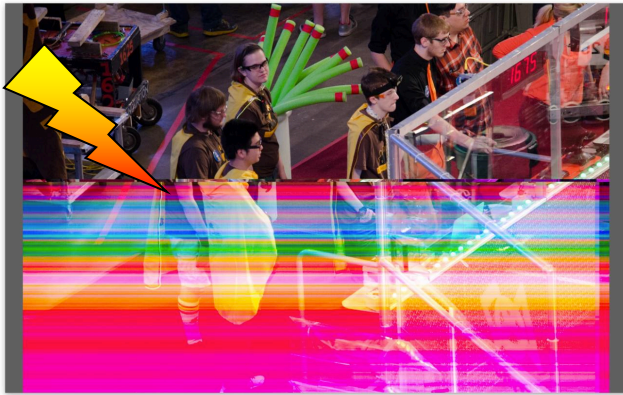
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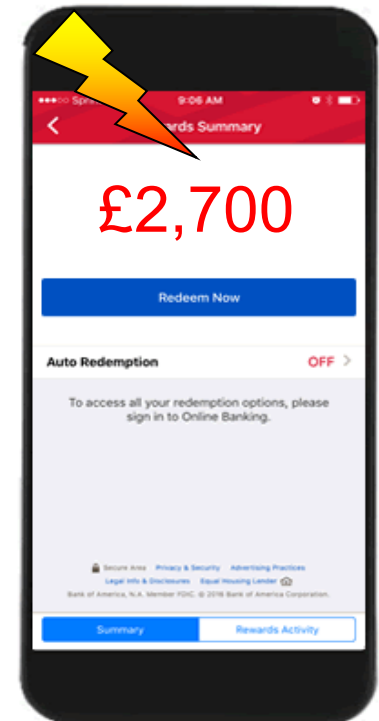
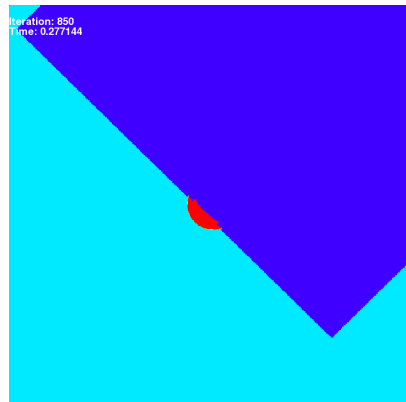
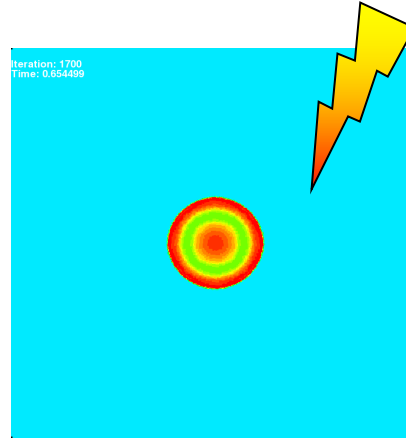
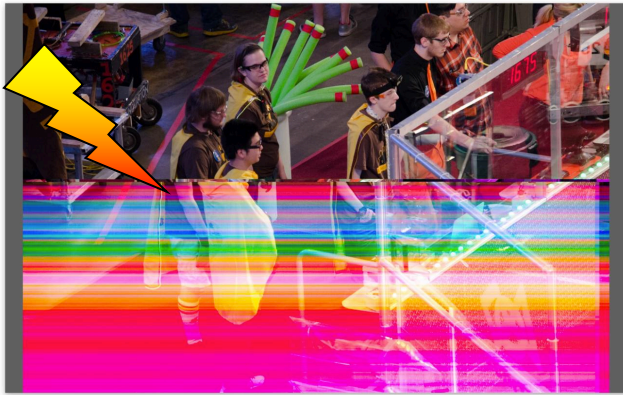
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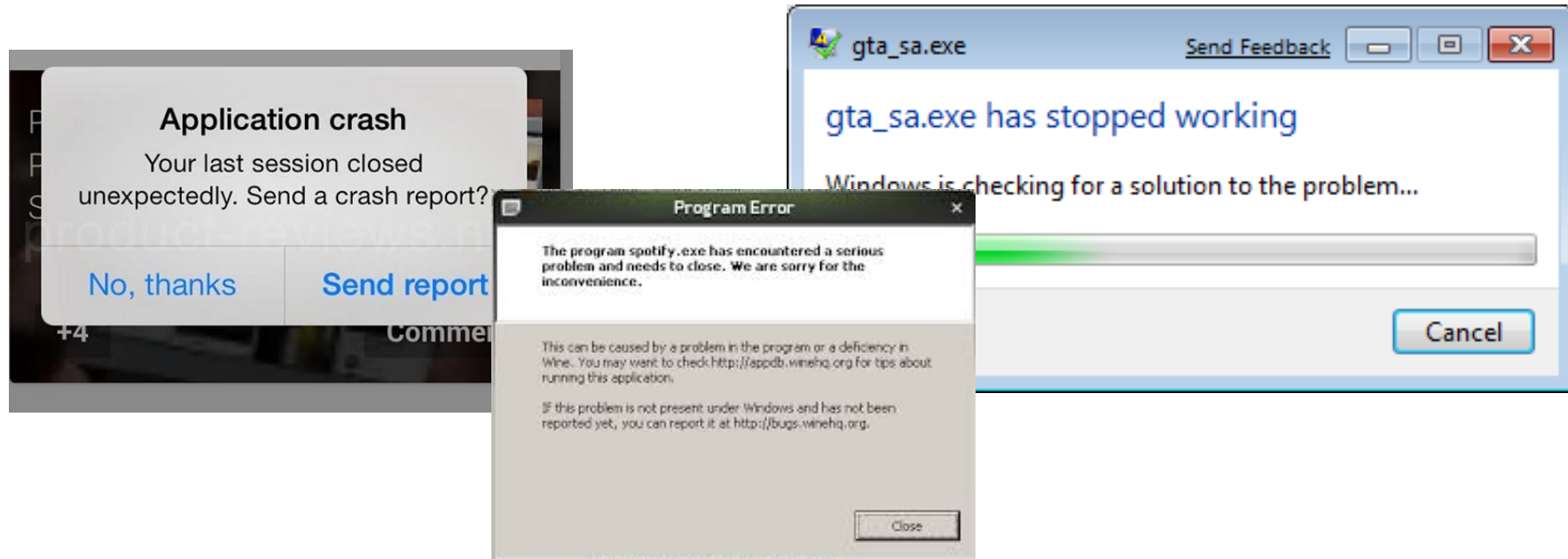
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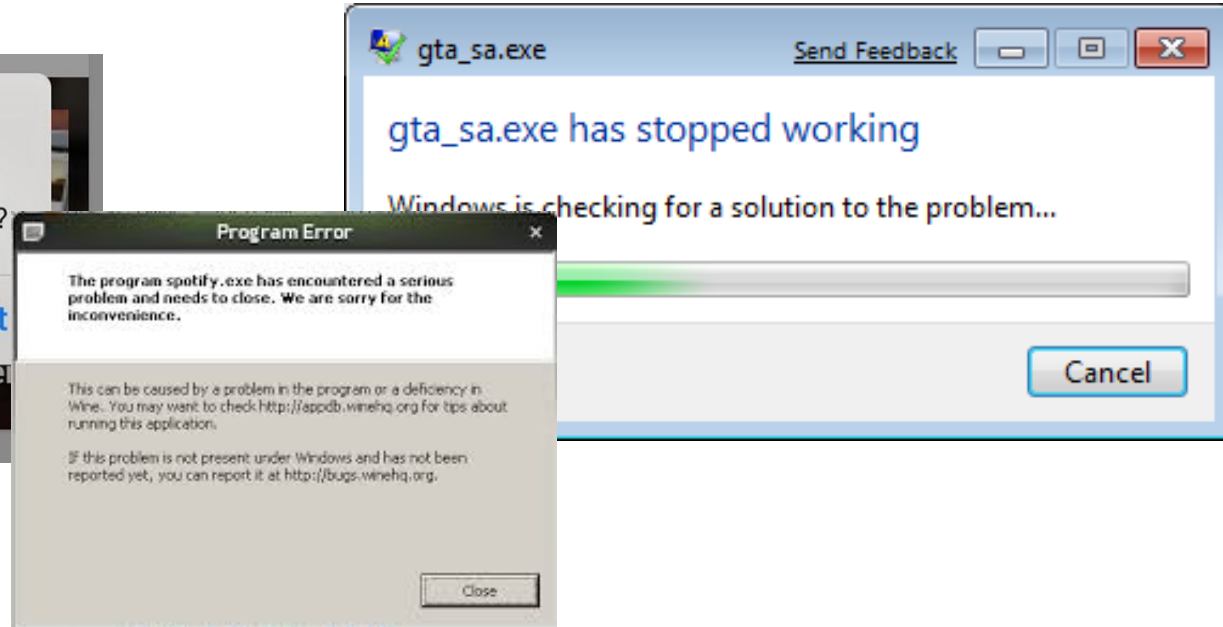
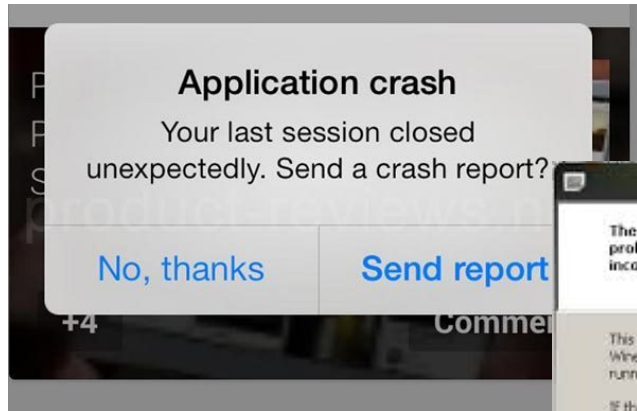
Silent Data Corruption vs Crash

Neutron-induced faults can also induce
Application Crash or Device Reboot



Silent Data Corruption vs Crash

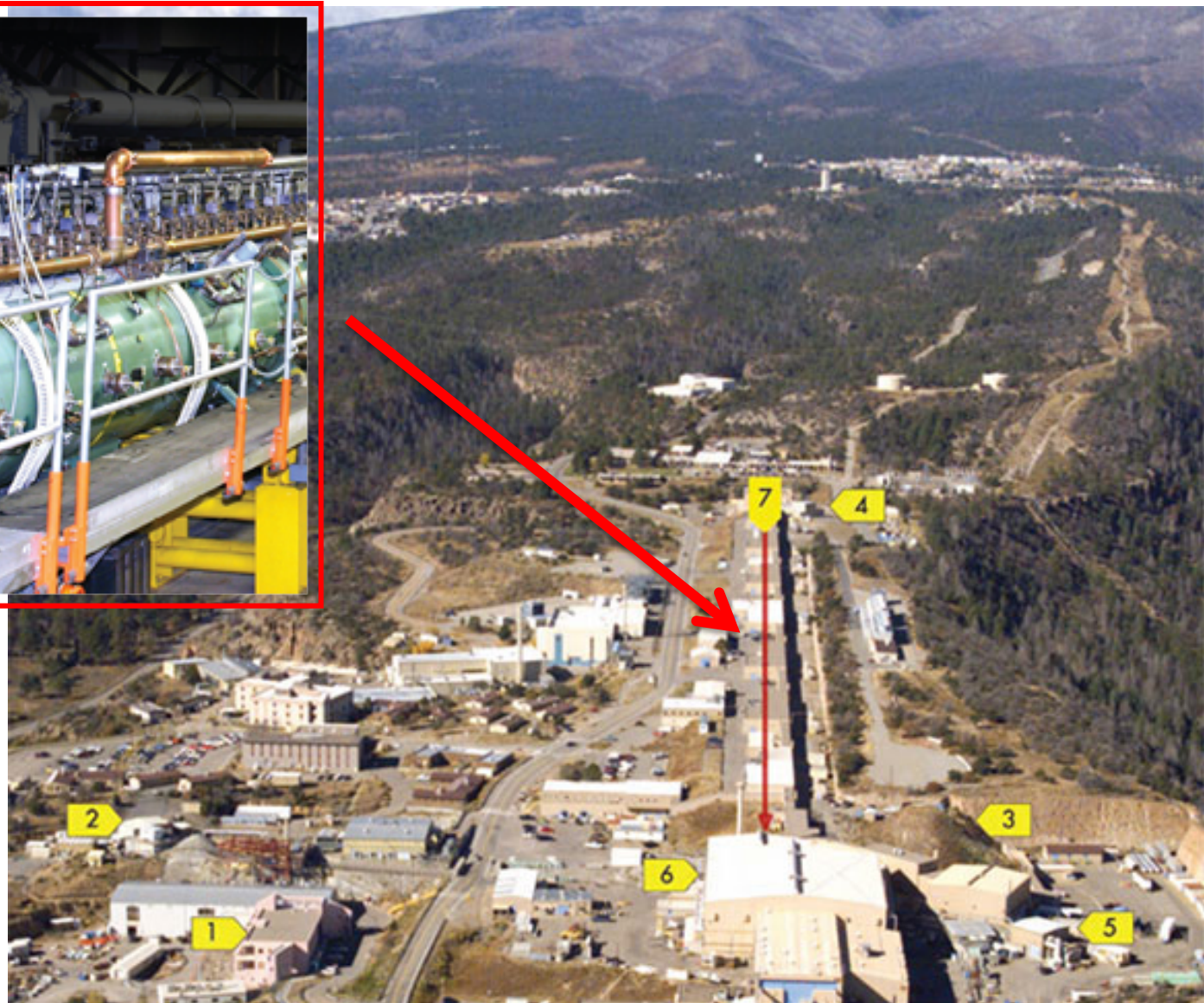
Neutron-induced faults can also induce
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Don't (always) blame Microsoft/Apple

- Why neutrons disturb computing devices
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Radiation Test Facilities

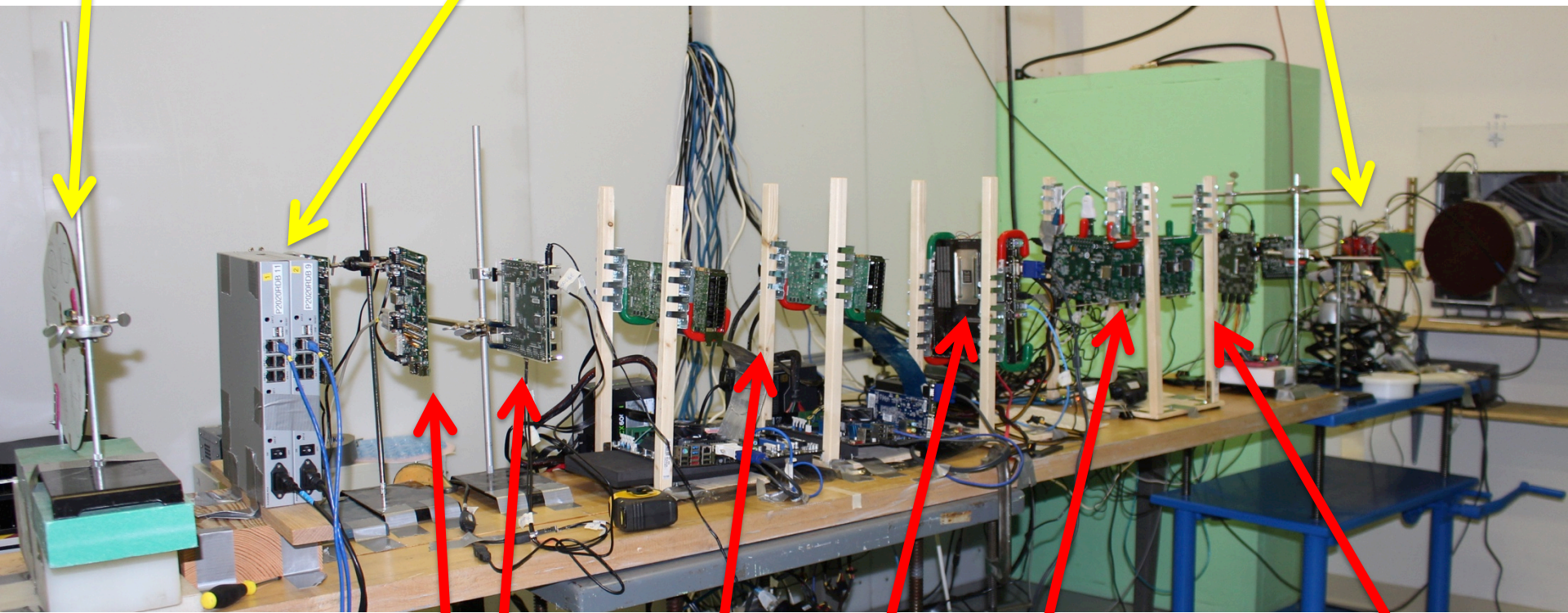


LANSCCE Dec. 2016 test

Flash

SoC

microcontrollers



FPGAs

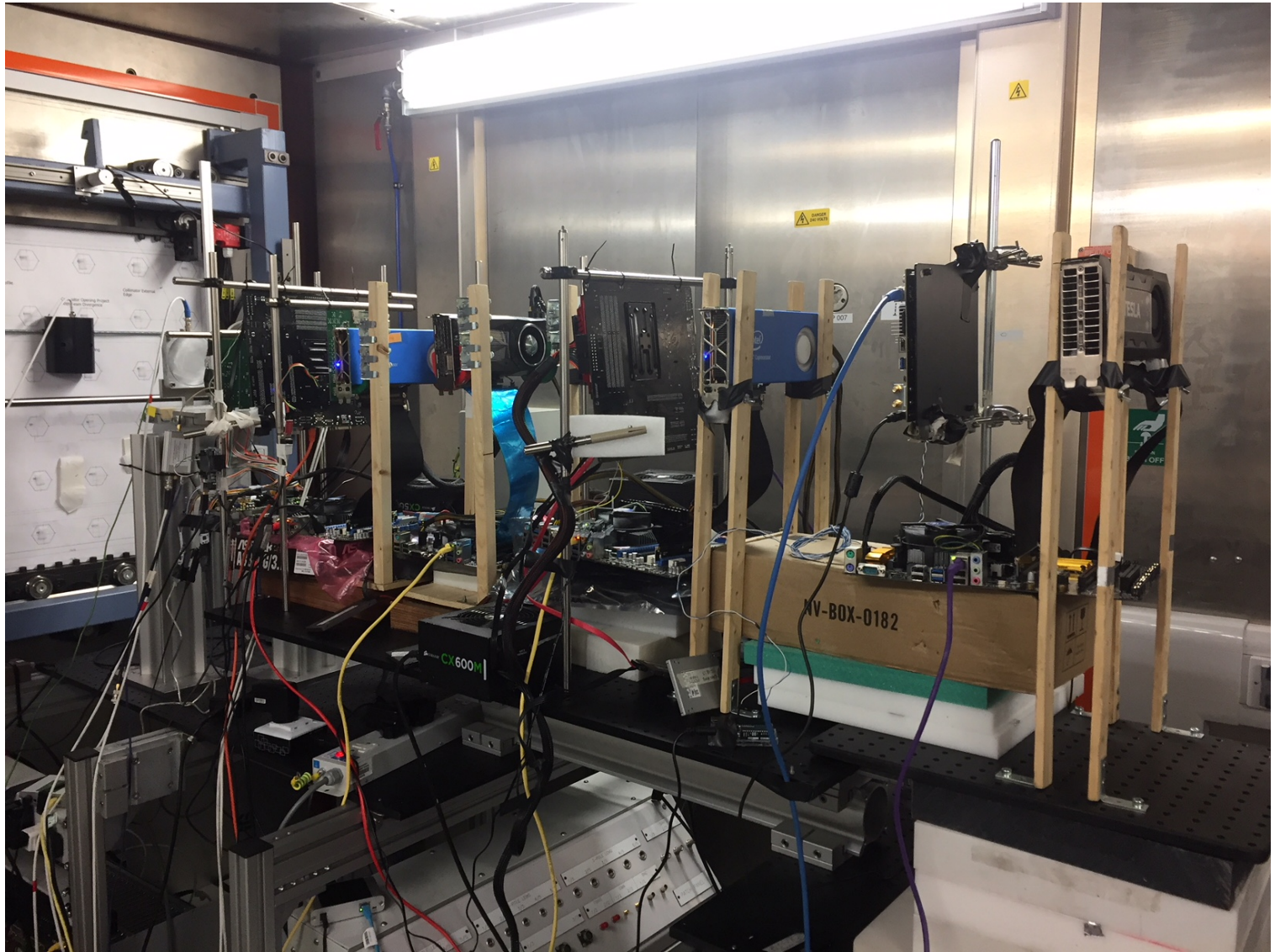
GPUs

APU

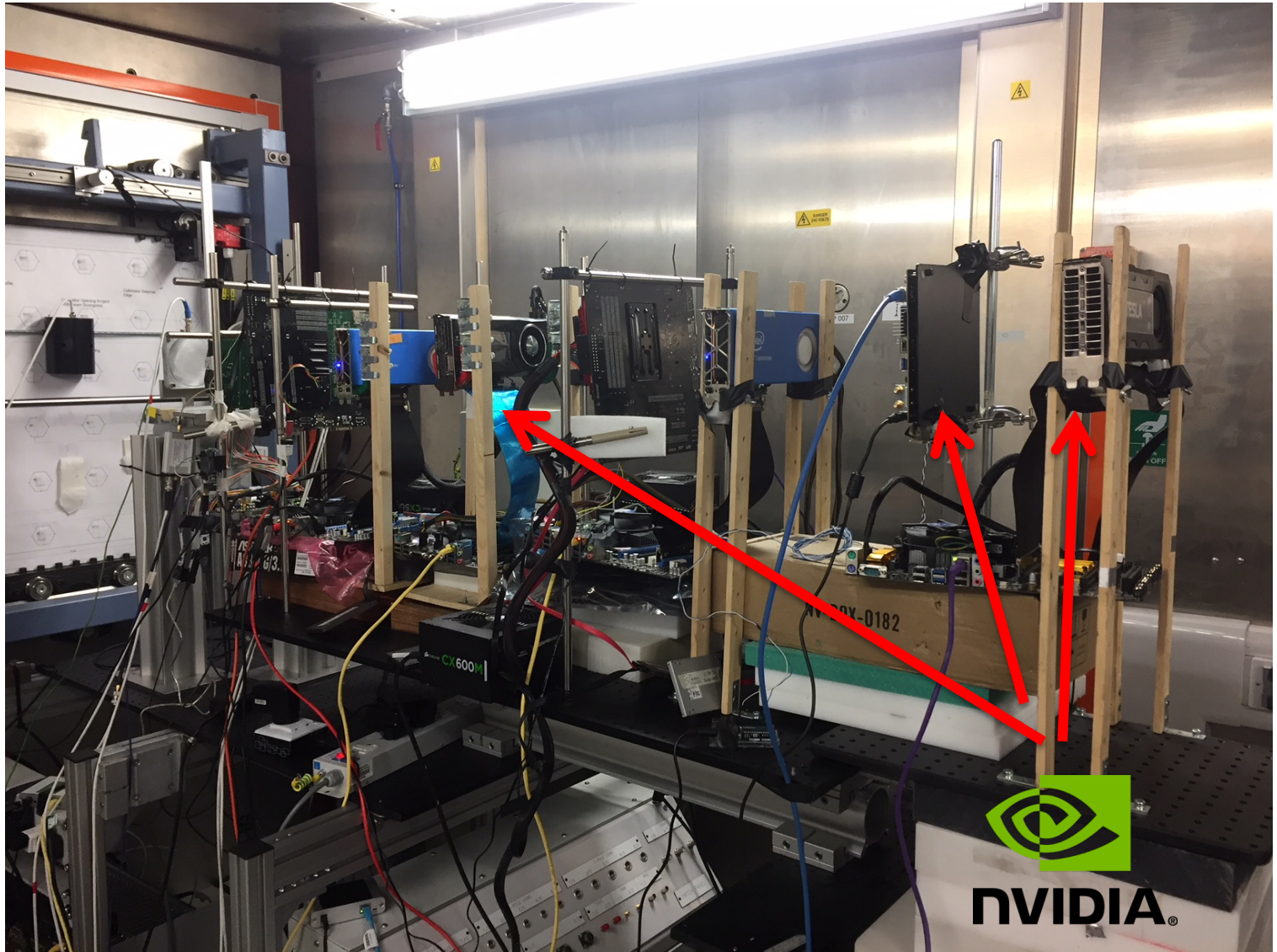
4x SoCs

2x FPGAs

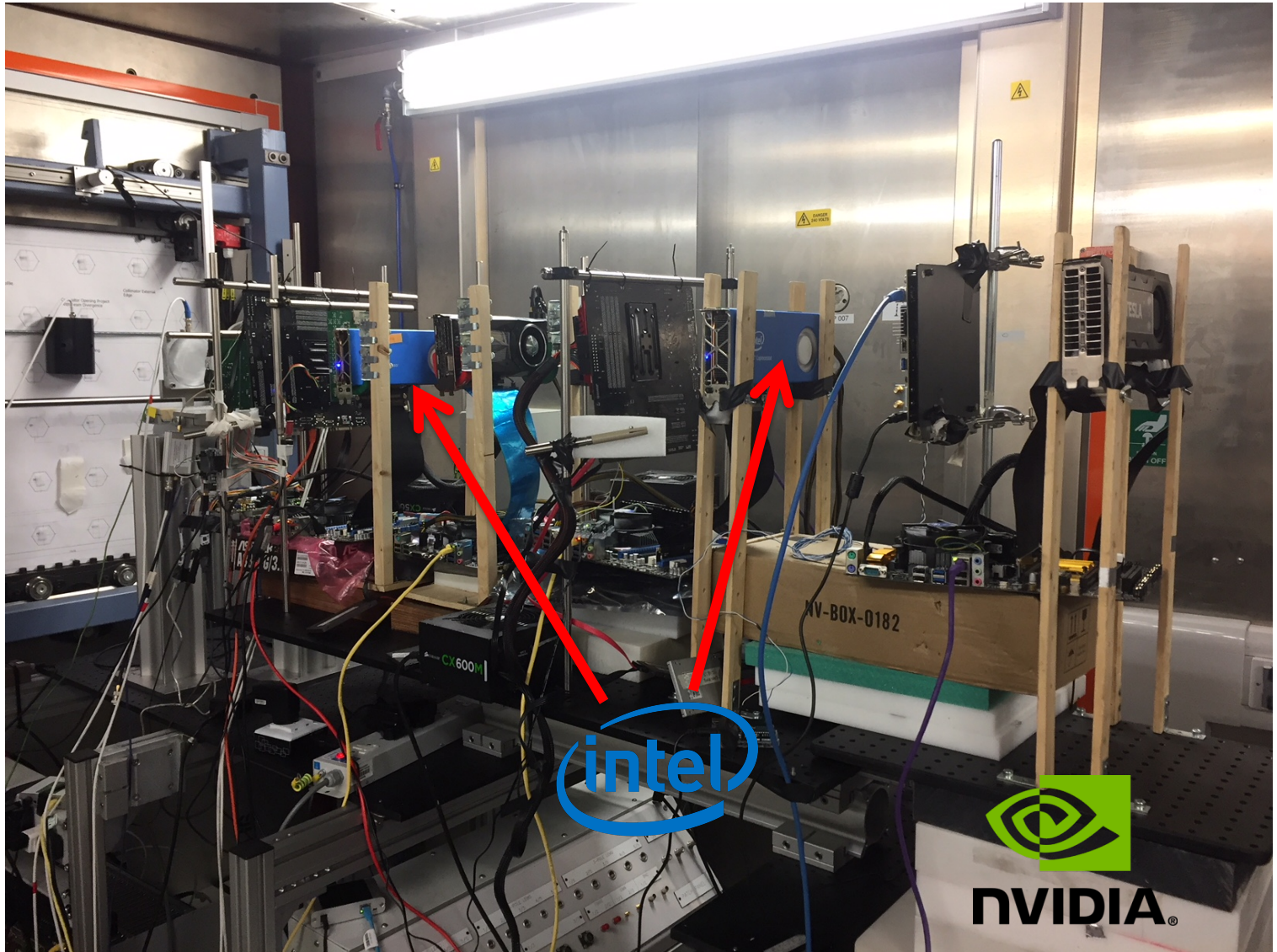
Experiment @ChiplR



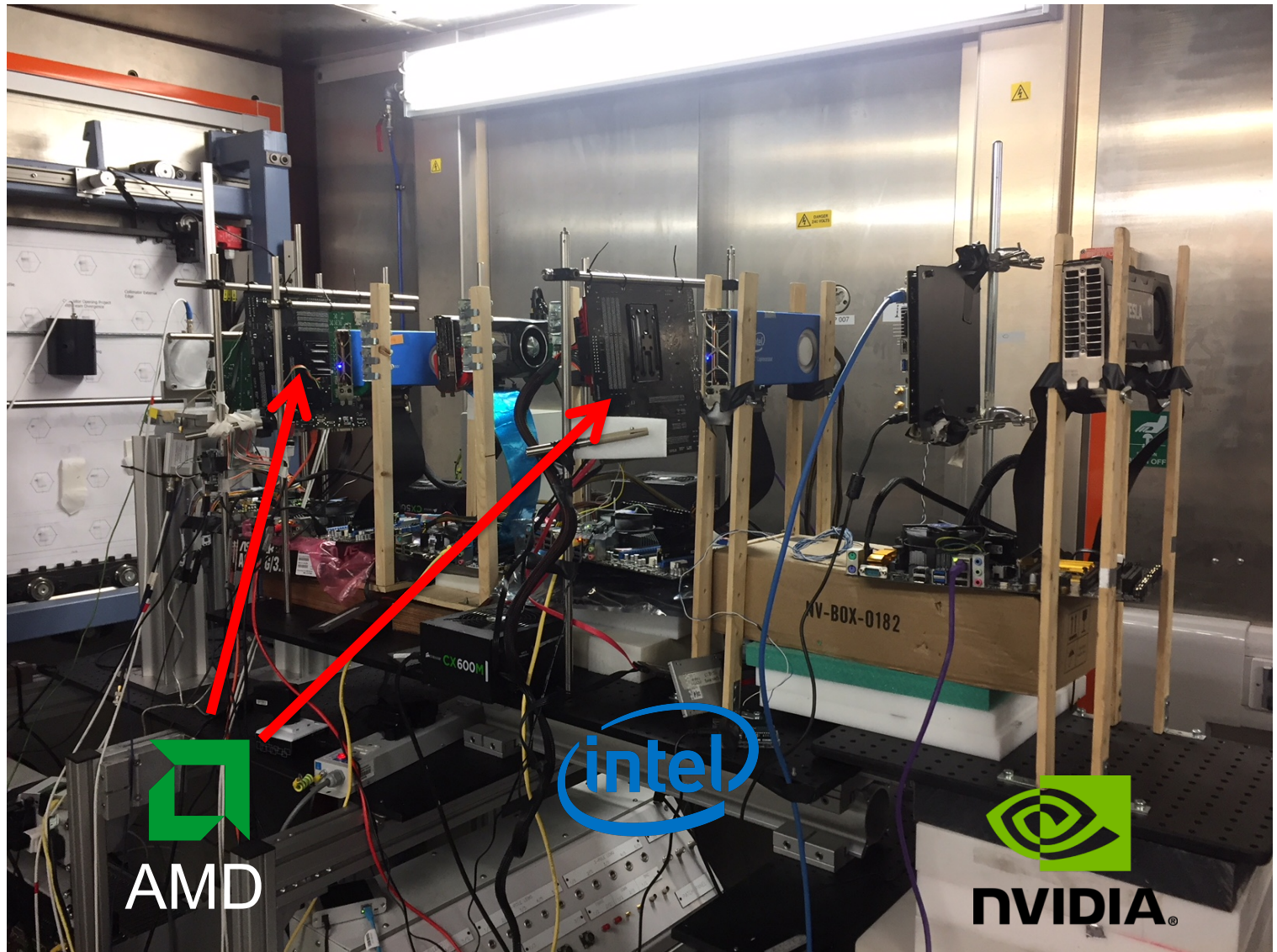
Experiment @ChipIR



Experiment @ChiplR



Experiment @ChipIR

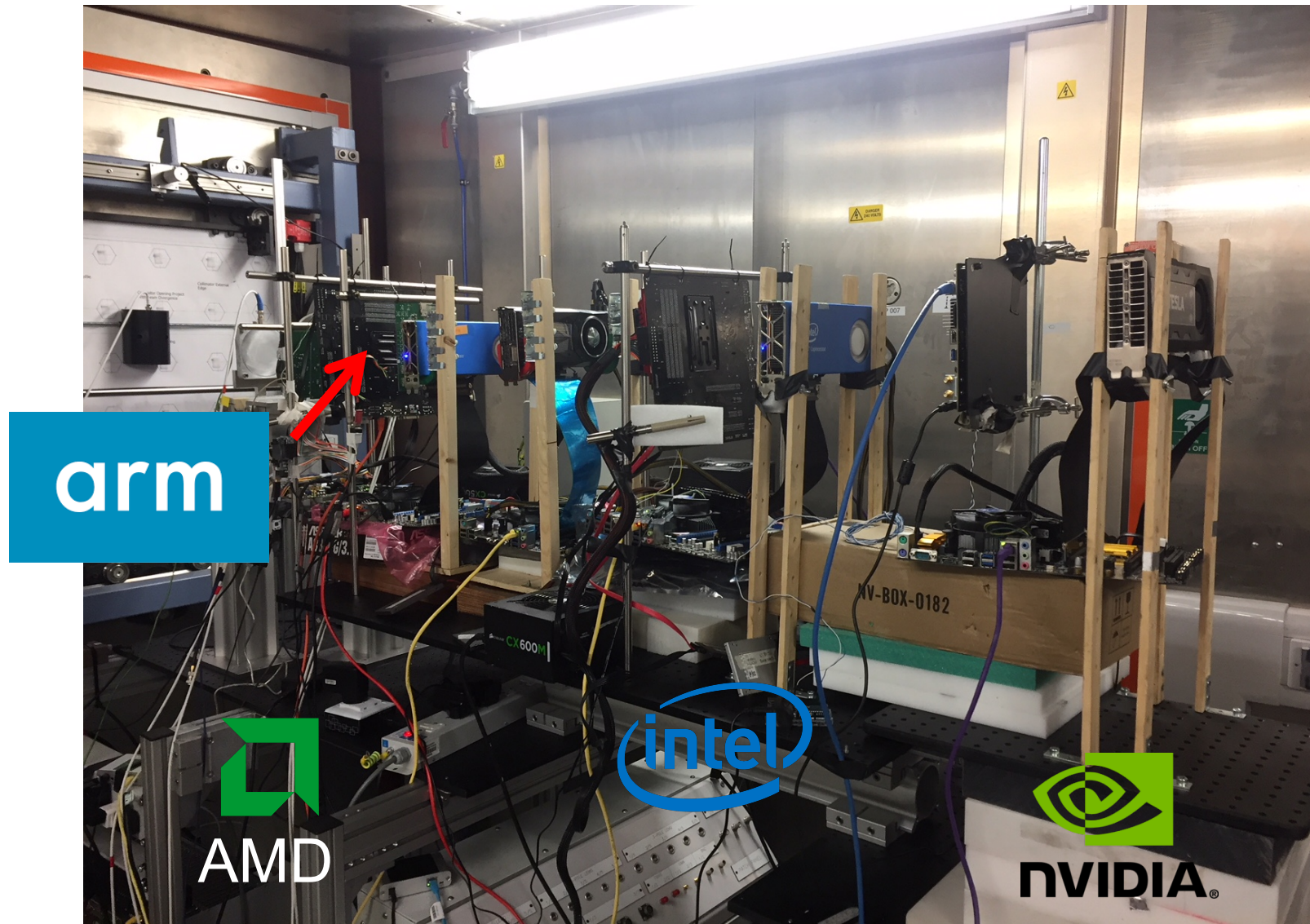



AMD


intel

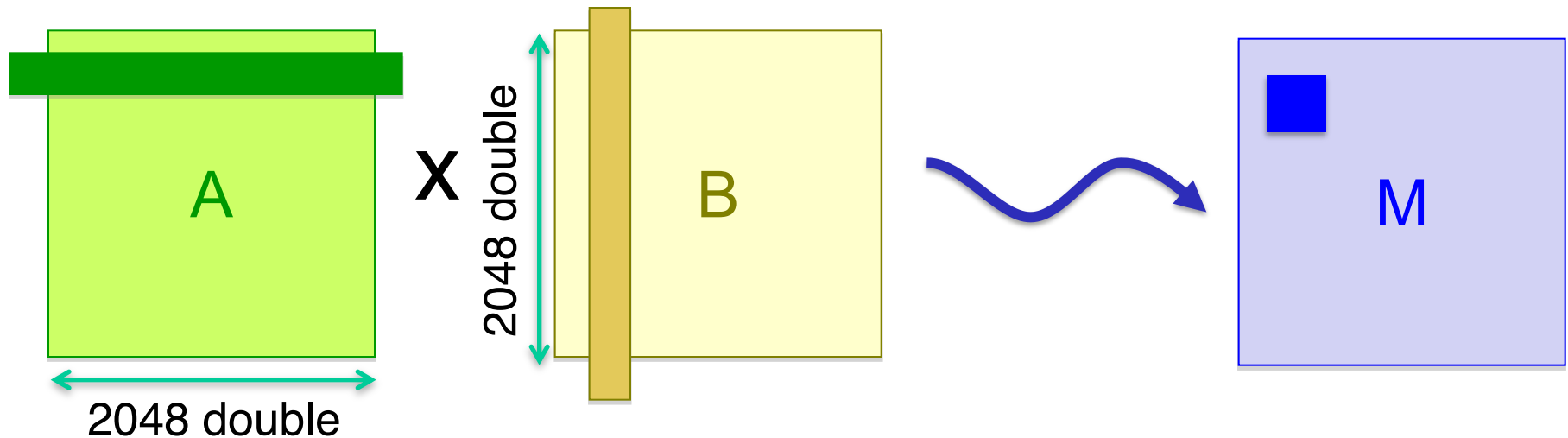

nvidia®

Experiment @ChiplR



Radiation Sensitivity

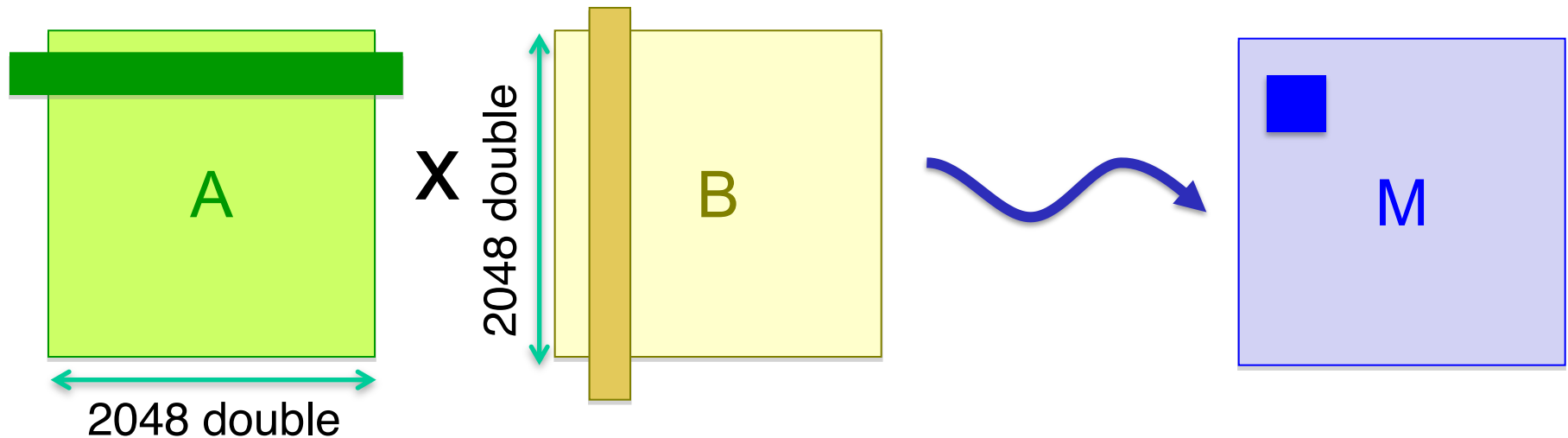
Example: Matrix Multiplication on “Device A”



Cross Section • **flux (@sea level)** = **Error Rate**

Radiation Sensitivity

Example: Matrix Multiplication on “Device A”

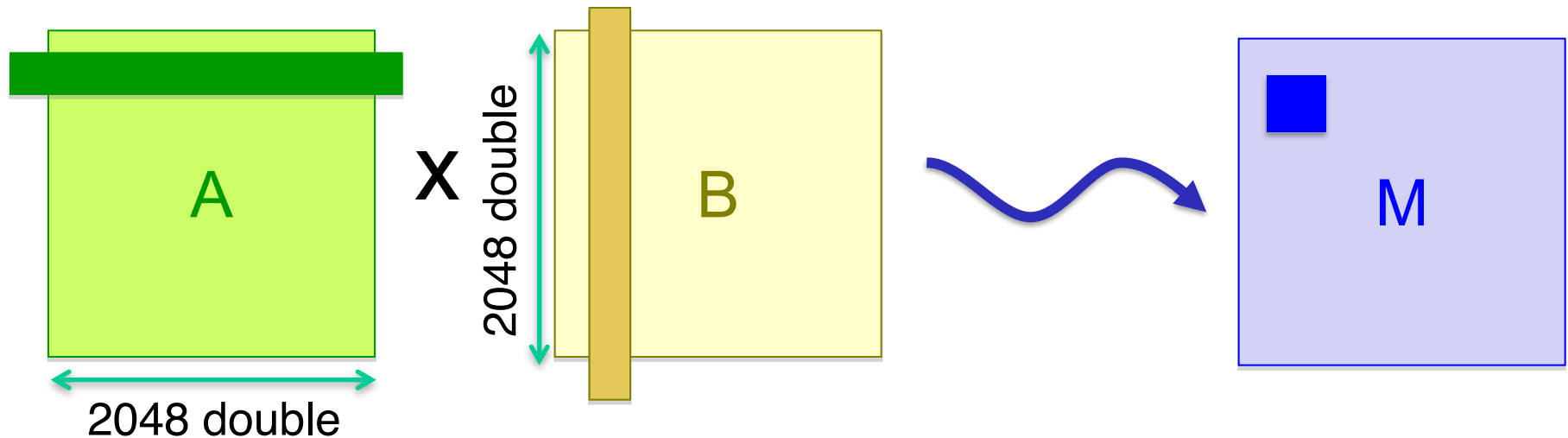


Probability for 1 neutron to generate an error

$$\text{Cross Section} \cdot \text{flux (@sea level)} = \text{Error Rate}$$

Radiation Sensitivity

Example: Matrix Multiplication on “Device A”



Cross Section • **flux (@sea level)** = **Error Rate**

$$2.66 \cdot 10^{-6} \text{ cm}^2 \cdot 13 \text{ n/cm}^2/\text{h} = 3.46 \cdot 10^4 \text{ FIT}$$

1 error every 3,2 years

Cars in the USA



There are **~280 millions cars** in the USA right now

On the average, according to the American Driving Survey, 8% of cars are on the move: ~22.4 millions cars

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22.4×10^6 errors every 3.2 years...

...~776 errors per hour

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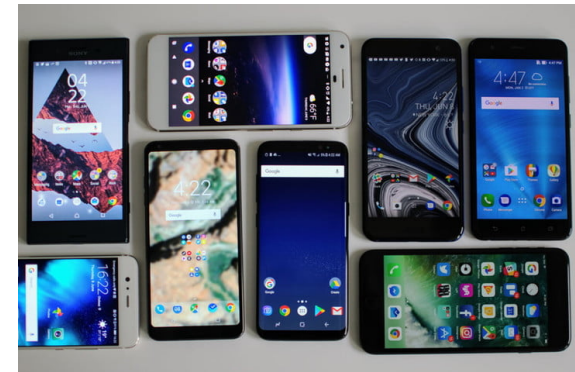
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22.4×10^6 errors every 3.2 years...

...~776 errors per hour

...there are **~260 millions** mobile phones in the USA



Feelings about radiation

“Soft errors have become a huge concern in advanced computer chips because, uncorrected, they produce a failure rate that is higher than all the other reliability mechanisms combined!”

R. Baumann, IEEE-TDMR, 2005

“Since chip SER is viewed by many as a legal liability (selling something that you know may fail), the public literature in this field is sparse and always makes management nervous”

J. Ziegler and H. Puchner, “SER-History, Trends and Challenges”, Cypress Semiconductors, 2004

Feelings about radiation


“...None of the four laboratories produced conversion factors that agreed with each other within a factor of 100%, and the maximum difference was about 3000 times. **It was a sad day for scientific reproducibility.**”

J. Ziegler, “Terrestrial Thermal Neutrons”,
IEEE TNS 2003

and always makes management nervous”

*J. Ziegler and H. Puchner, “SER-History,
Trends and Challenges”, Cypress
Semiconductors, 2004*

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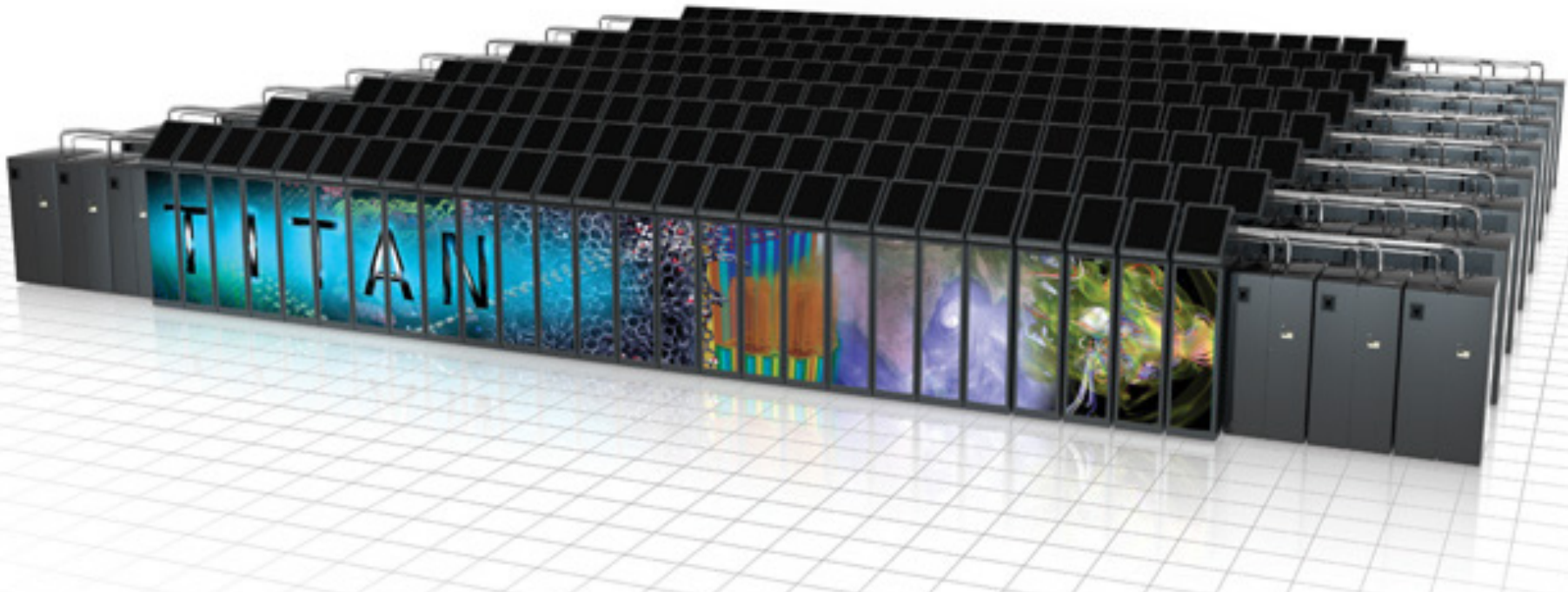


“Fan Facts” about neutron-induced errors

Who has to worry about
radiation induced soft errors?

TITAN error rate

**TITAN supercomputer has 18,000 devices:
18,000 errors every 3,2 years:
14 errors per day!**

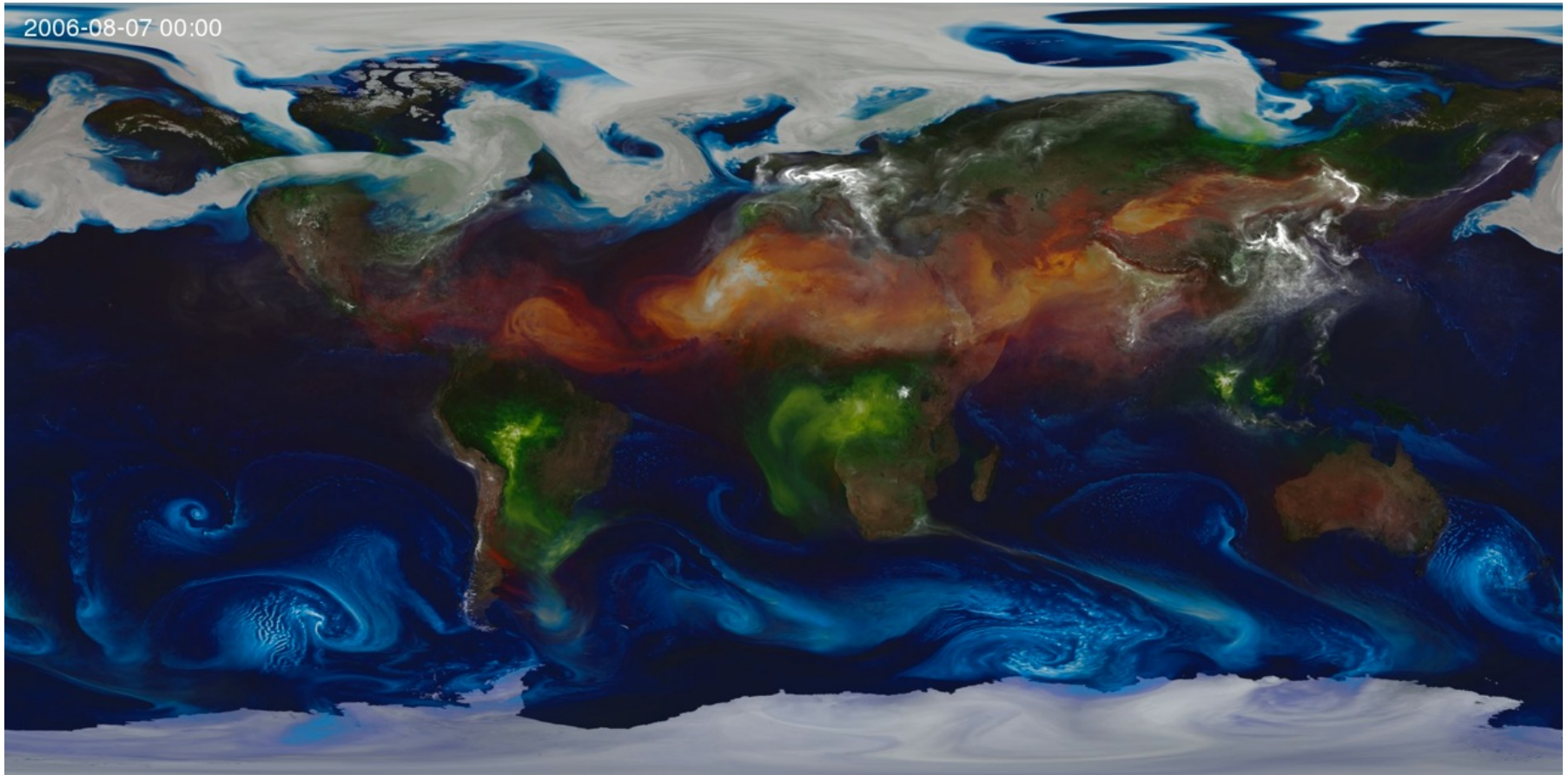


Supercomputer SDC example

January 2012

Simulation of environmental effects in the atmosphere over time

Expert scientist (Daniel Duffy @ NASA GSFC) visually identified a high amount of sea salt aerosol in the atmosphere in the simulation



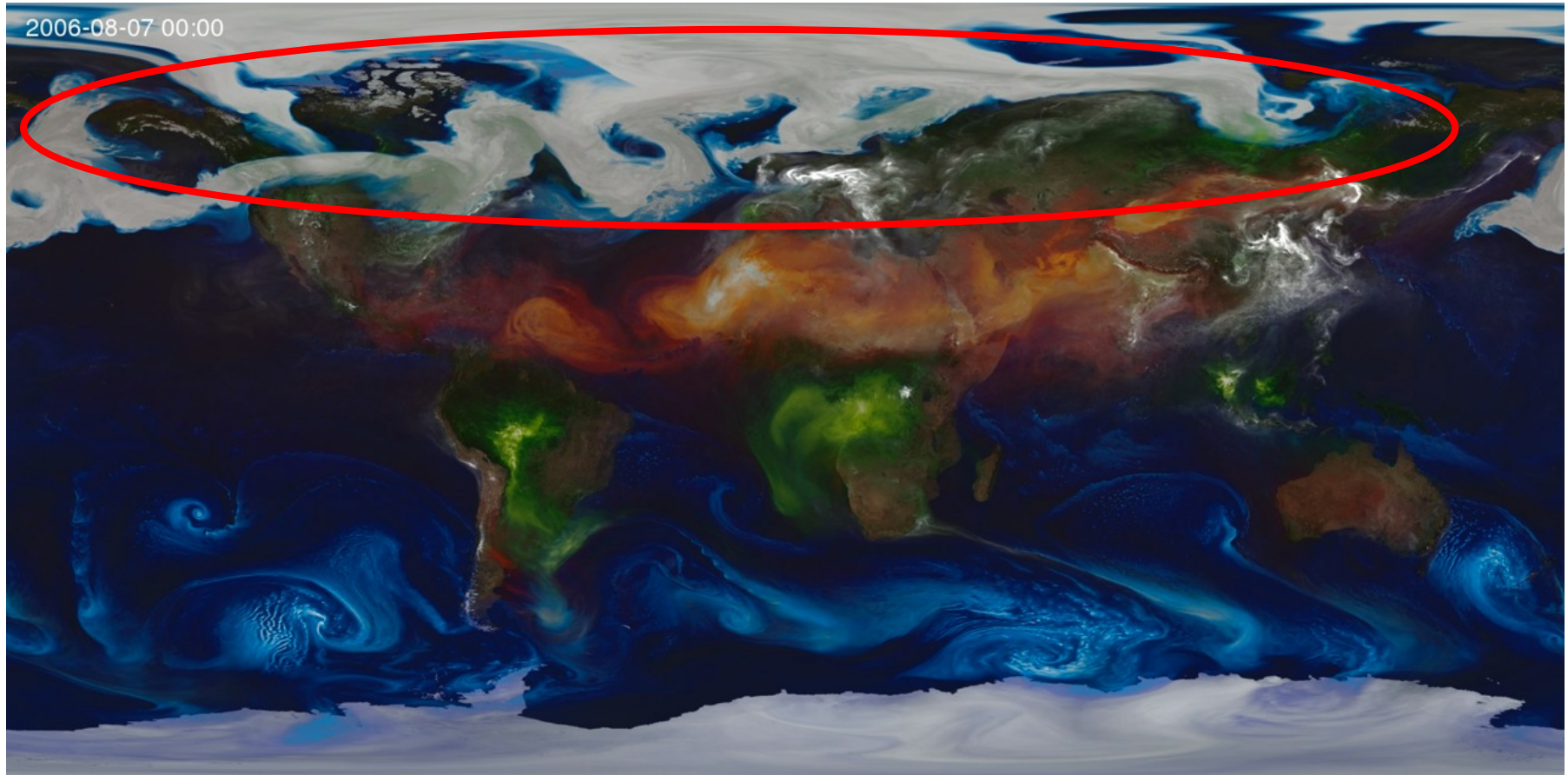
*courtesy Sean Blanchard, LANL

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*courtesy Sean Blanchard, LANL

HPC bad stories

Virginia Tech's Advanced Computing facility built a supercomputer called Big Mac in 2003

- 1,100 Apple Power Mac G5
- Couldn't boot because of the failure rate
- Power Mac G5 did not have error-correcting code (ECC) memory
- Big Mac was broken apart and sold on-line



Jaguar – (2009 #1 Top500 list) ● 360 terabytes of main memory ● 350 ECC errors per minute

ASCI Q – (2002 #2 in Top500 list)

- Built with AlphaServers
- 7 Teraflops
- Couldn't run more than 1h without crash
- After putting metal side it could last 6h before crash
- Address bus on the microprocessors were unprotected (causing the crashes)

Aerospacial Applications

Radiation is certainly an issue for those developing aerospace and military applications



Levels of radiation in space and very high altitudes are much higher than at earth surface

Quantas 72 A330 accident, Dec. 2008



Politics as well... the Brussels case

Maria Vindevoghel



2003 elections:

due to a cosmic ray
she gained 4,096
extra votes.

It is becoming a (personal) concern

Assicurato ha diritto all'indennizzo di invalidità permanente a condizione che la stessa si manifesti entro due anni dall'Infortunio.

La valutazione dell'invalidità permanente sarà effettuata in base alla lesione che segue nella pagina successiva. Se la lesione comporta una diminuzione anziché la perdita anatomica o funzionale di un organo o arti, le percentuali della tabella vengono ridotte in proporzione alla funzionalità residua.

In caso di perdita totale anatomica o funzionale di più organi od arti, si applica l'applicazione di una tabella di invalidità pari alla somma delle singole percentuali arrotondate per eccesso, con un massimo del 100%. Per i casi non previsti dalla tabella, il grado di

ART. C.3 - ESCLUSIONI

Sono esclusi dall'assicurazione i sinistri determinati da:

a) partecipazione a corse o gare e relative prove ufficiali e verifiche preliminari e finali previste nel regolamento particolare di gara;

b) tumulti popolari, atti di terrorismo, vandalismo, attentati ai quali l'Assicurato abbia partecipato attivamente;

c) guerra, insurrezioni, terremoti, eruzioni vulcaniche;

d) trasmutazione del nucleo dell'atomo come pure dovuti ad esposizione a radiazioni ionizzanti;

ART. C.4 - LIQUIDAZIONE

den un'eccezione all'angolo di un arto del piede un arto inferiore all'altezza di sotto al ginocchio o un occhio ambedue gli occhi un rene la milza sordità completa di un orecchio sordità completa di ambedue gli orecchi perdita totale dell'udito voce postumi di trauma distorsione cervicale con contrattura muscolare limitazione dei movimenti del capo del collo

Liquidazione incaricato dalla Società di giustizia oppure intervento Sanità quota prede anticipata sanita presenza incarico danno

The insurance does not cover those accidents caused by:

[...]

exposure to ionizing radiation*

****Paolo's car insurance***

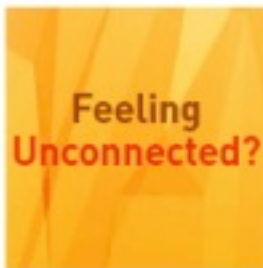
Automotive Applications

Soft Error leading to a single bit flip caused a fatal error in 2007



BREAKING NEWS

NEWS & ANALYSIS: Module Boost Indoor Tracking Accuracy



designlines **AUTOMOTIVE**

News & Analysis

Toyota Case: Single Bit Flip That Killed

Junko Yoshida

10/25/2013 03:35 PM EDT

102 comments

14 saves
[LOGIN TO RATE](#)

Automotive Applications

Soft Error leading to a single bit flip caused a fatal error in 2007

What's the new trend in the Automotive Market???



Feeling
Unconnected?

designlines AUTOMOTIVE

News & Analysis

Toyota Case: Single Bit Flip That Killed

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- What's next?

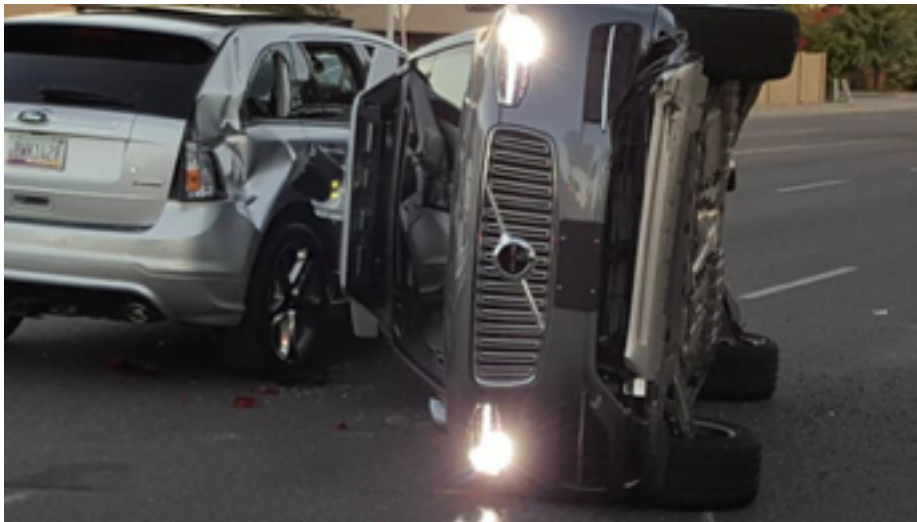
Self Driving Car

The new trend for automotive market is Self Driving Car!



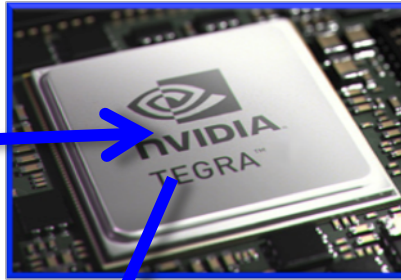
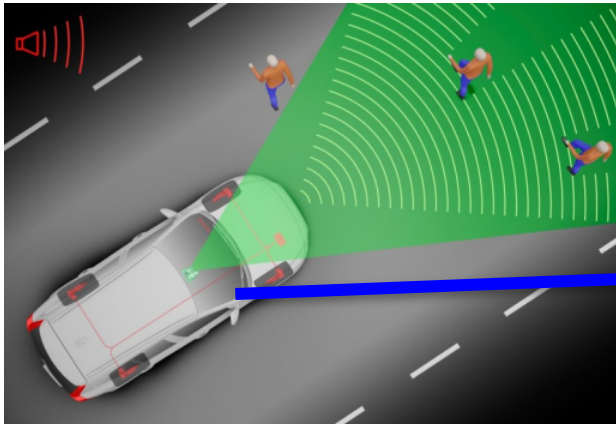
Self Driving Car

The new trend for automotive market is Self Driving Car!

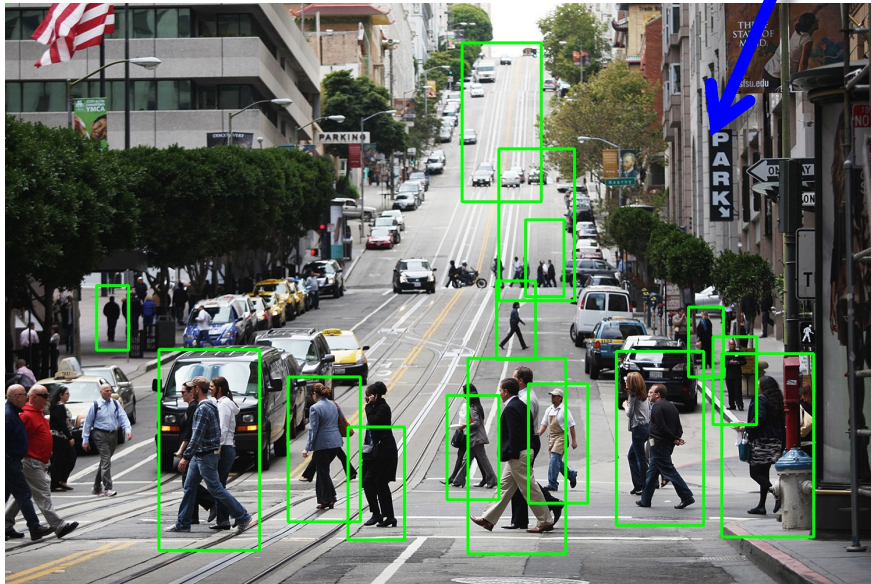


Neutron-induced errors

Objects Detection System:

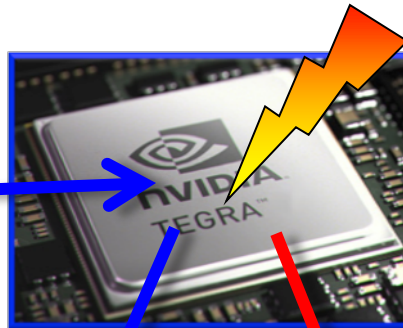
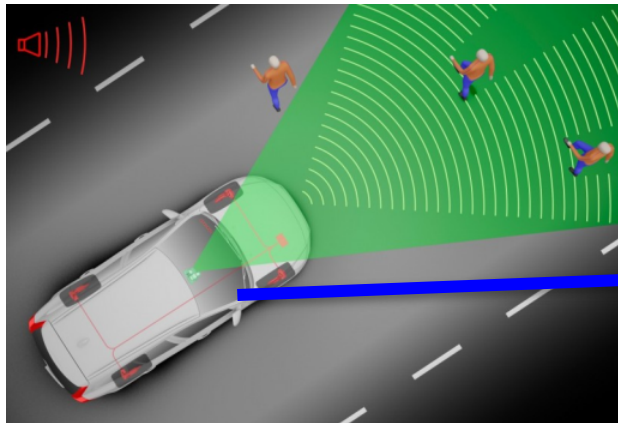


embedded GPUs
increase cars
security

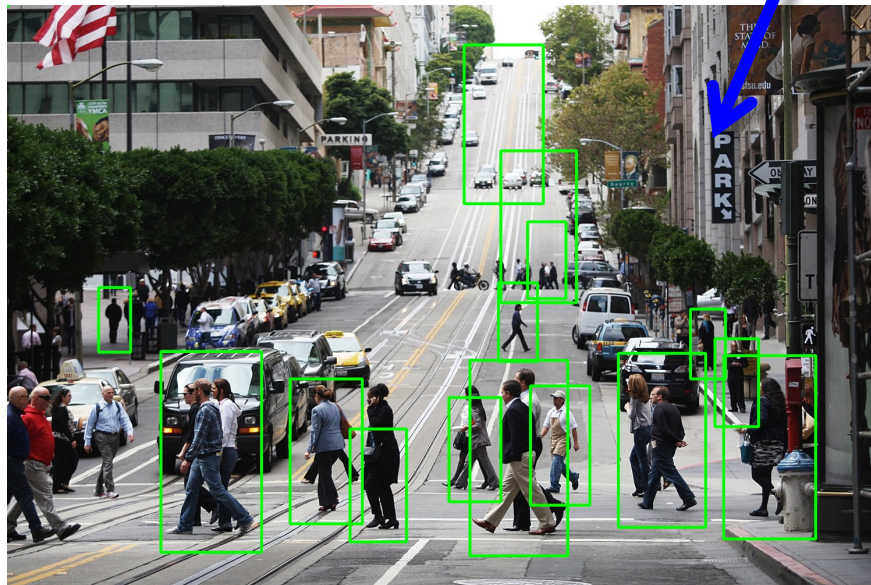


Neutron-induced errors

Objects Detection System:



embedded GPUs
increase cars
security



Observed error



Examples of observed errors



99% person
Expected

Examples of observed errors



Expected



Tolerable

Slight modification
of detection

Examples of observed errors

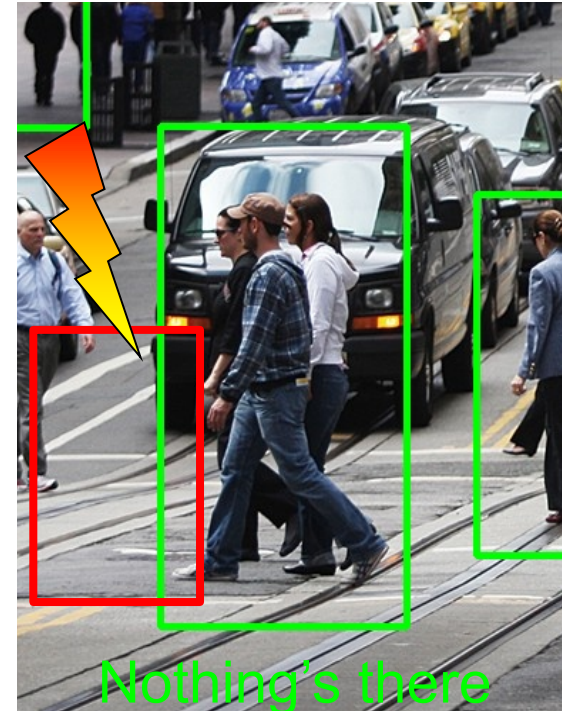


Expected



Tolerable

Slight modification
of detection



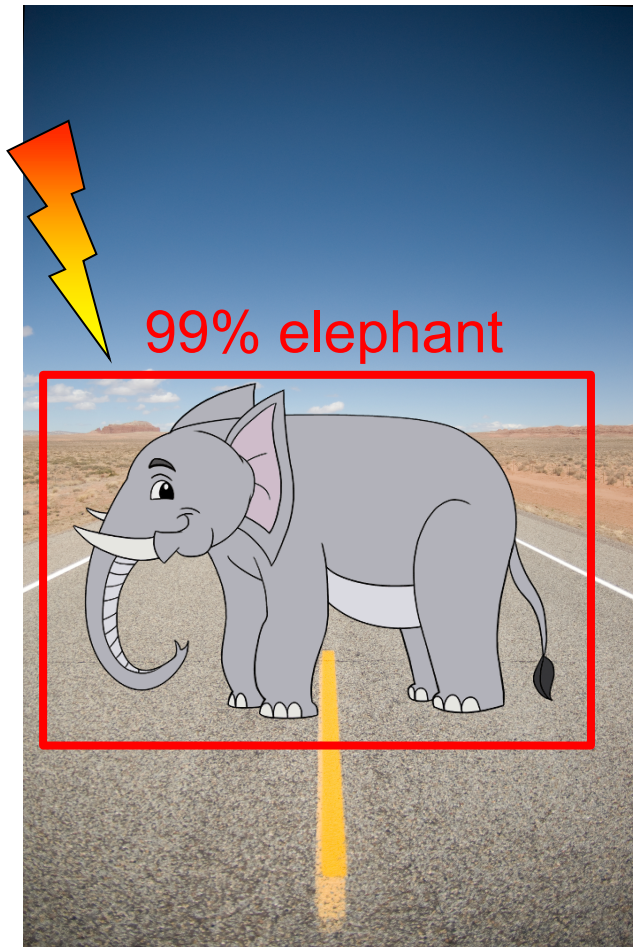
Critical

Missing an object

Examples of observed errors

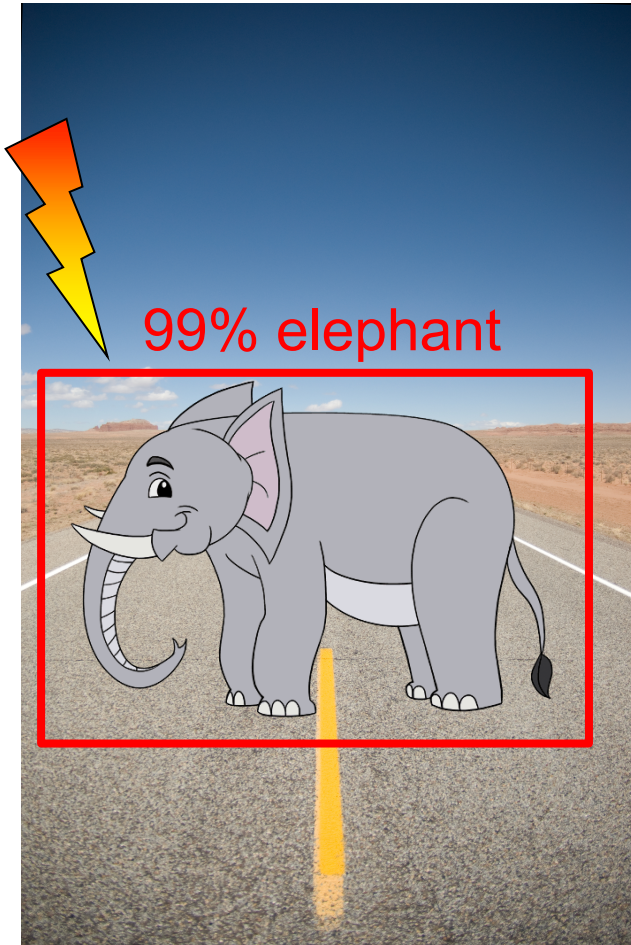


Examples of observed errors



False positive
Unnecessary stops

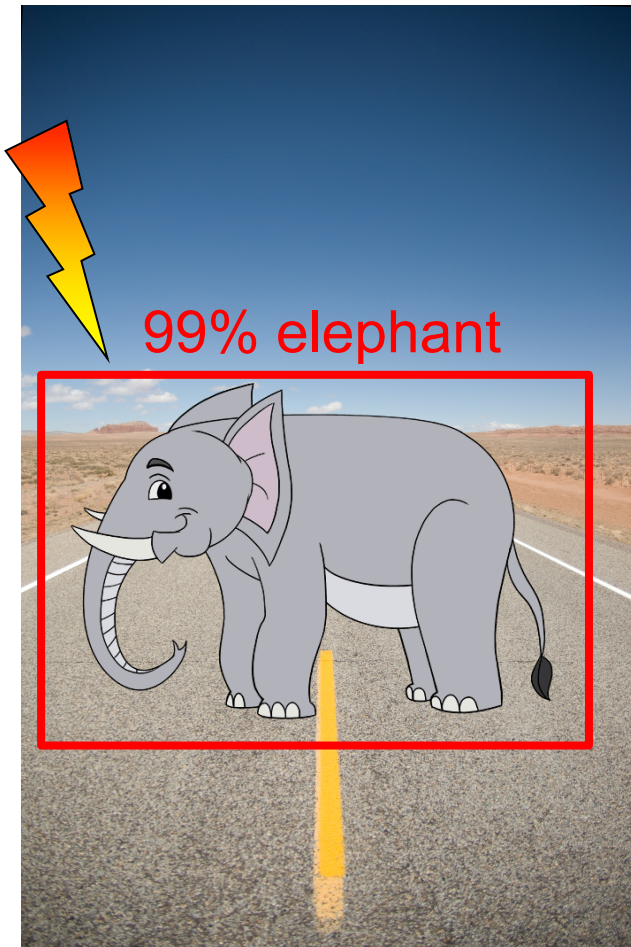
Examples of observed errors



False positive
Unnecessary stops



Examples of observed errors



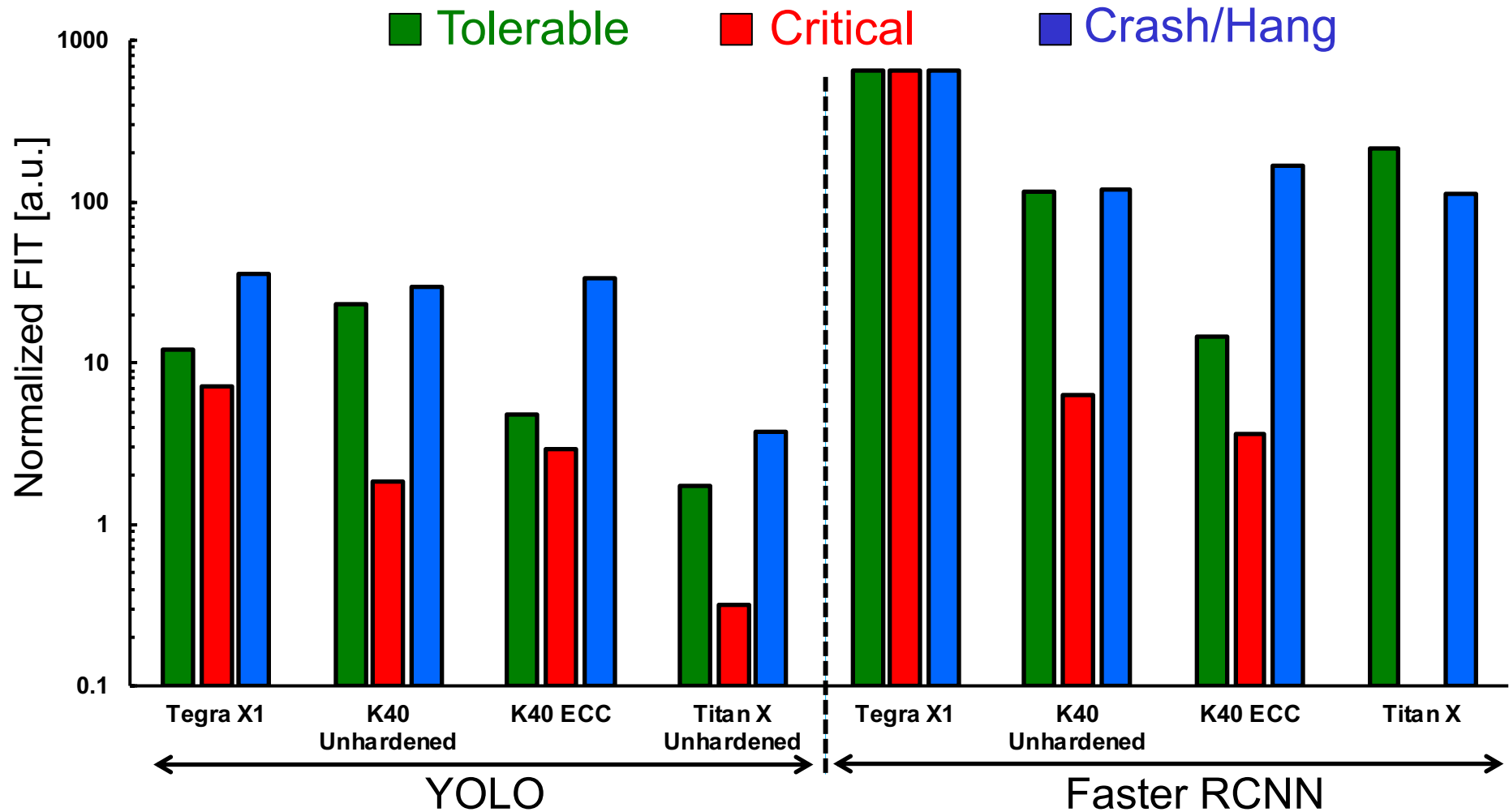
False positive
Unnecessary stops



*SC17 paper by BCU

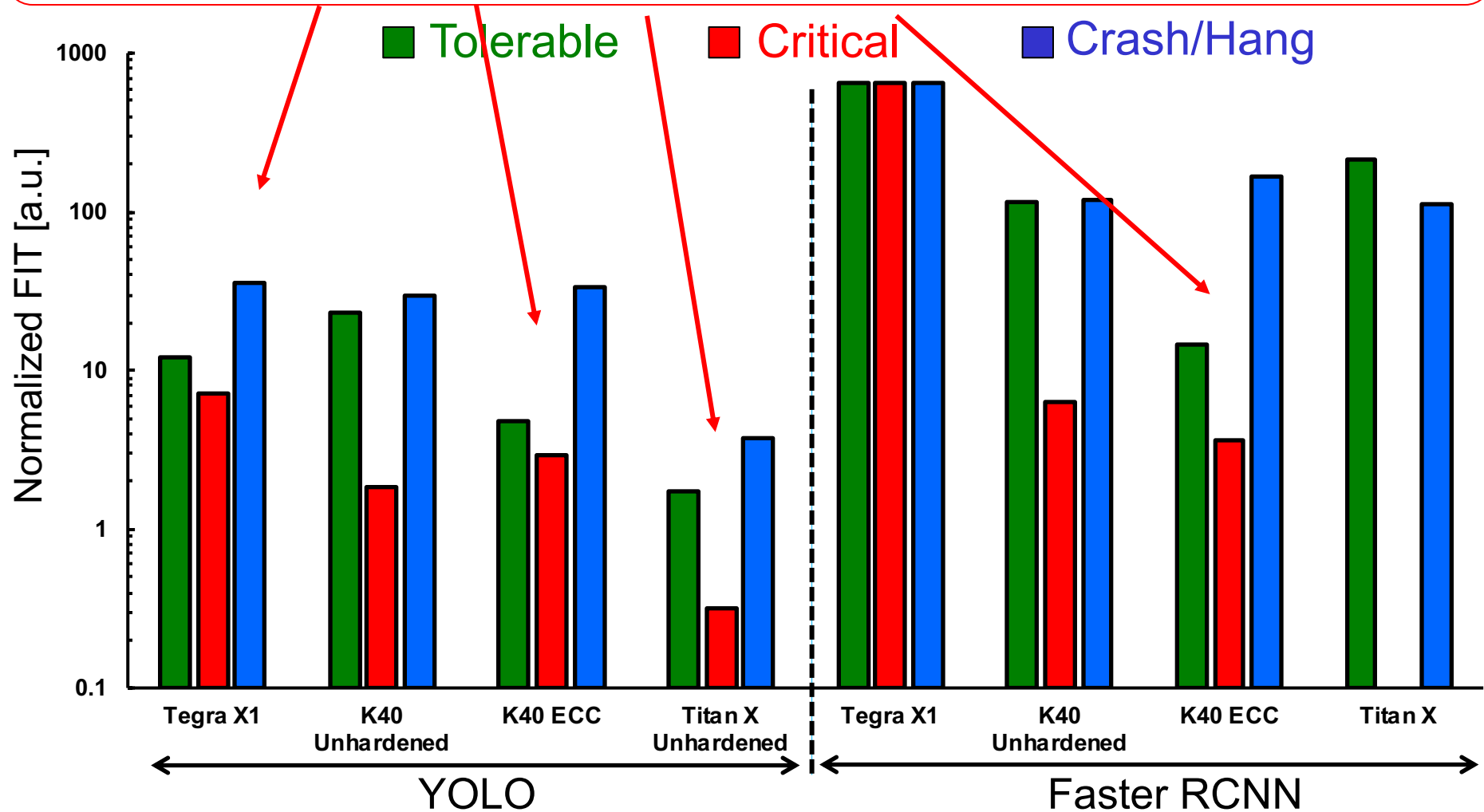
Classification Error
wrong object detects

Results – FIT



Results – FIT

Not all **SDCs** affect detection! **Critical SDCs** rate are 10x – 100x lower than **SDC rates**!



ISO26262 - Automotive Safety Integrity (ASIL)
level D, which is the highest classification of injury risk

- 1 – Detect 99% of permanent and transient faults
- 2 – Error rate < 10 FIT (10 errors in 10^9 h of operation)

Functional Safety

ISO26262 - Automotive Safety Integrity (ASIL)
level D, which is the highest classification of injury risk

- 1 – Detect 99% of permanent and transient faults
- 2 – Error rate < 10 FIT (10 errors in 10^9 h of operation)



1 system error (Feb. 2016) in
 1.5×10^6 miles driven
(60,000 h - 30,000 h driven)



16,000 – 23,000 FIT!

Functional Safety

ISO26262 - Automotive Safety Integrity (ASIL)
level D, which is the highest classification of injury risk

- 1 – Detect 99% of permanent and transient faults
- 2 – Error rate $< 10 \text{ FIT}$ (10 errors in 10^9 h of operation)



5,657,000 crashes caused by
human driver “error” in 2013 in
USA ($6 \times 10^{10} \text{ h}$ driven).

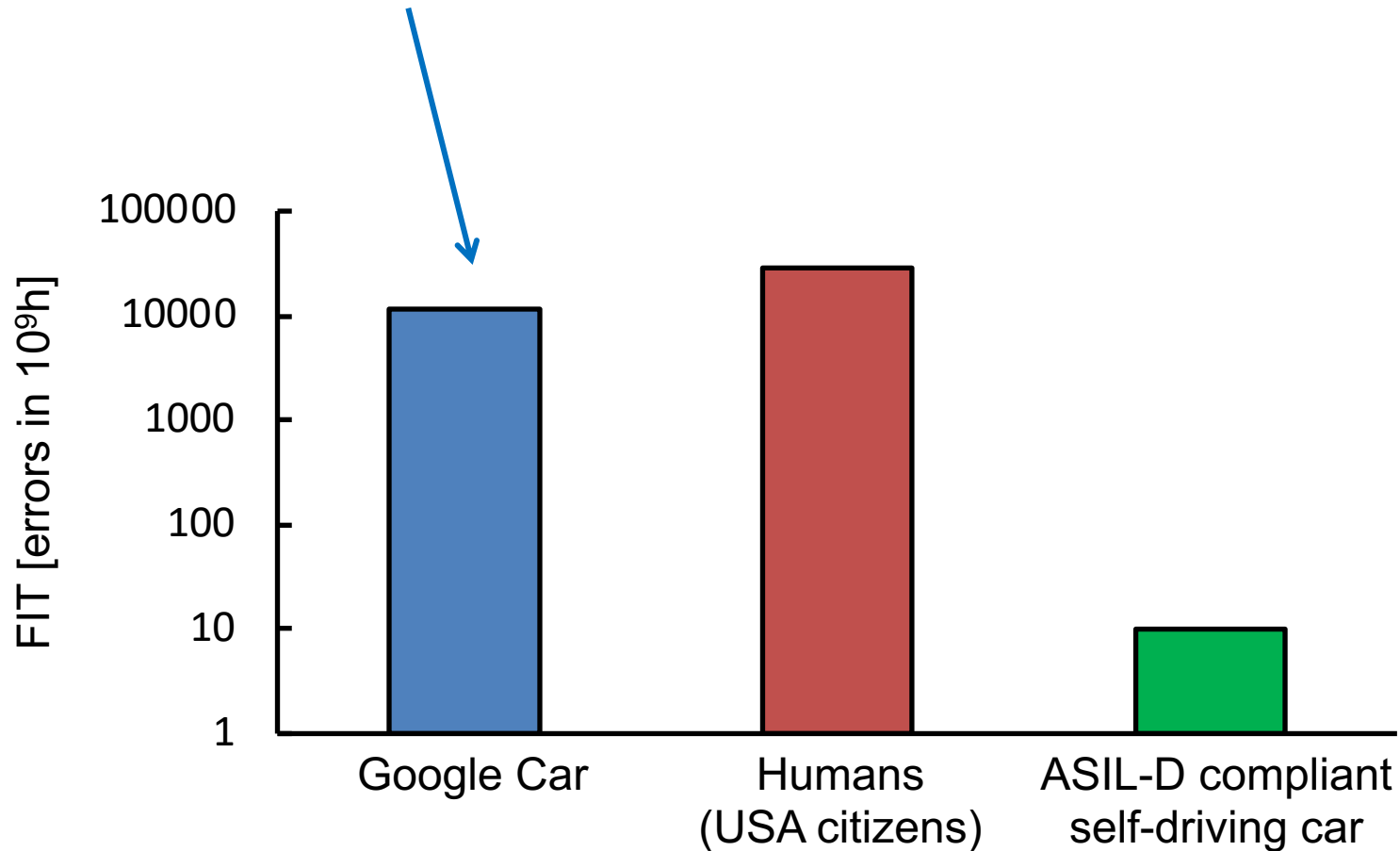


human driver error rate:
28,582 FIT!*

*Nirmal R. Saxena.
SELSE 2016 Keyonte

Functional Safety - review

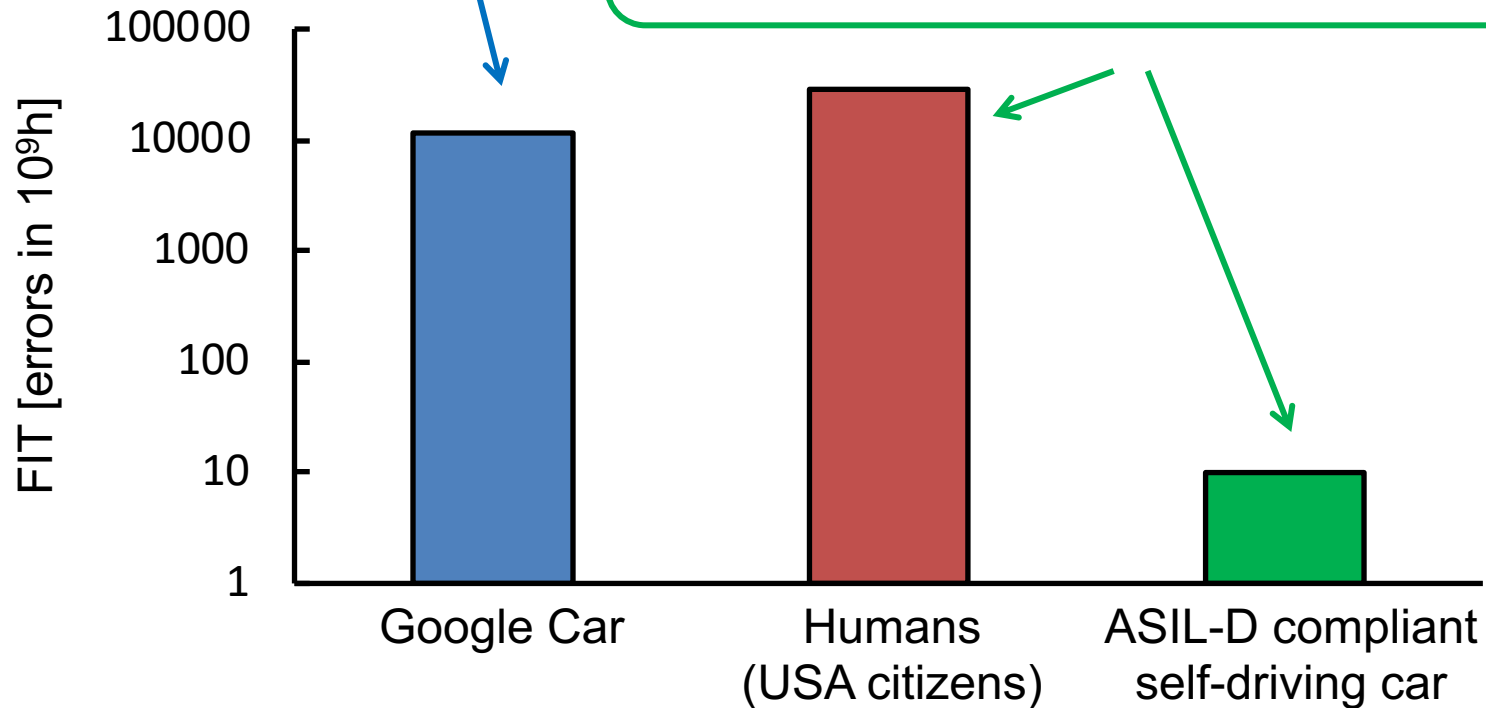
It is really challenging to design ASIL-D compliant self-driving systems



Functional Safety - review

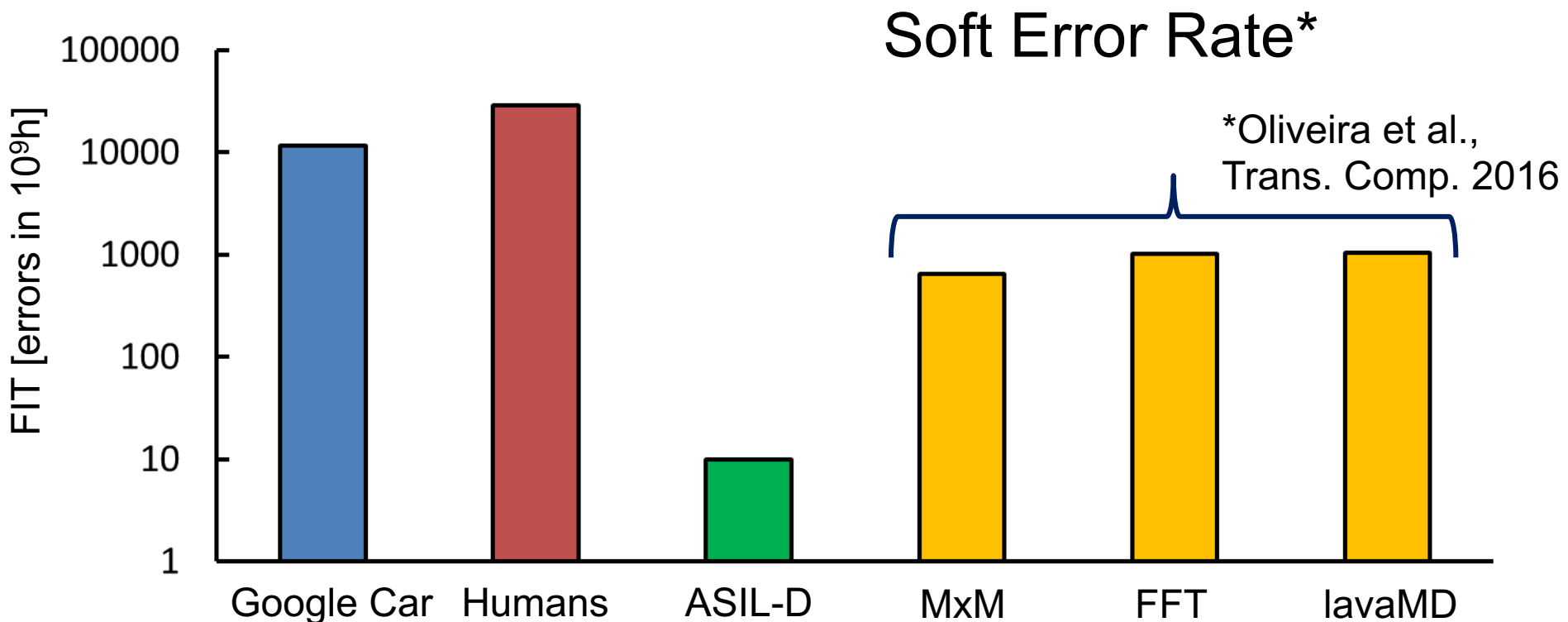
It is really challenging to design ASIL-D compliant self-driving systems

ASIL-D compliant self-driving cars could save a lot of lives

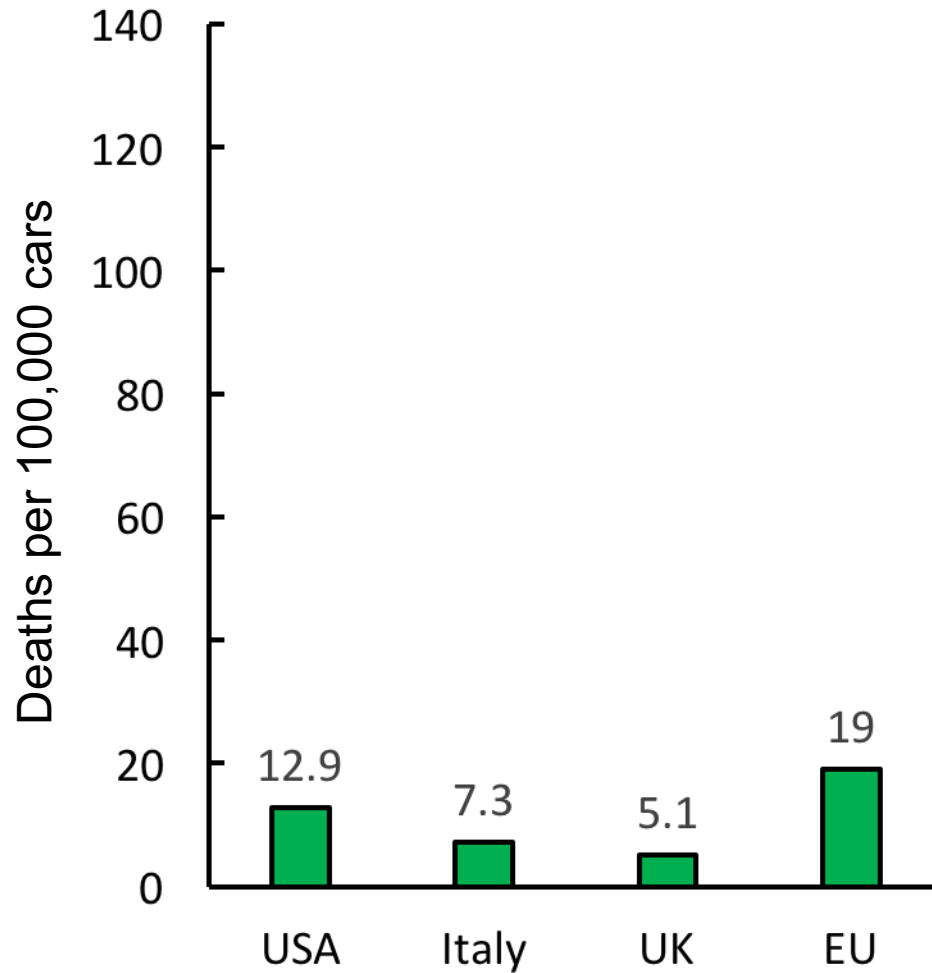


Radiation Issue for self-driven cars

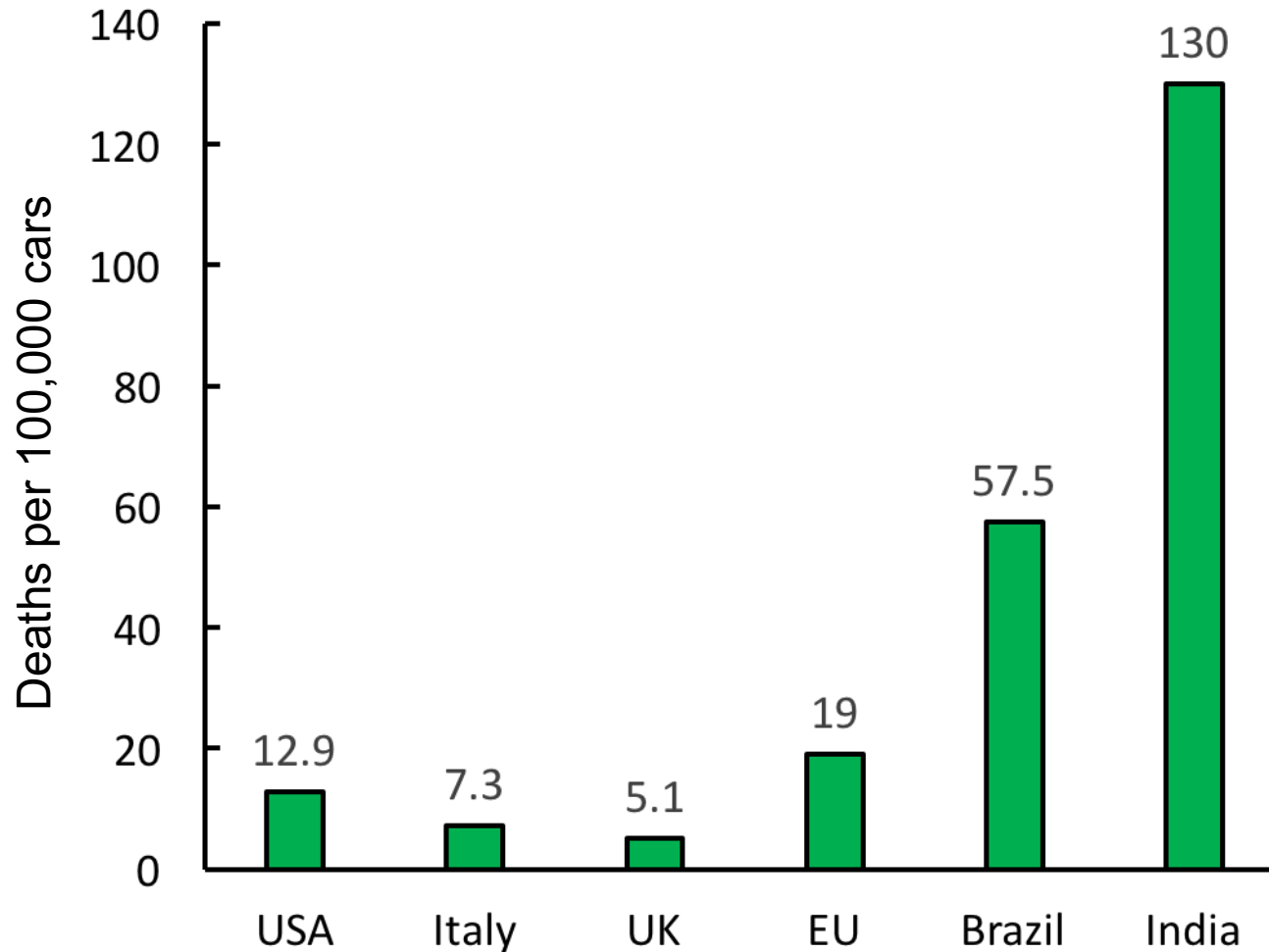
Computing devices architecture is designed to improve performances, not reliability.



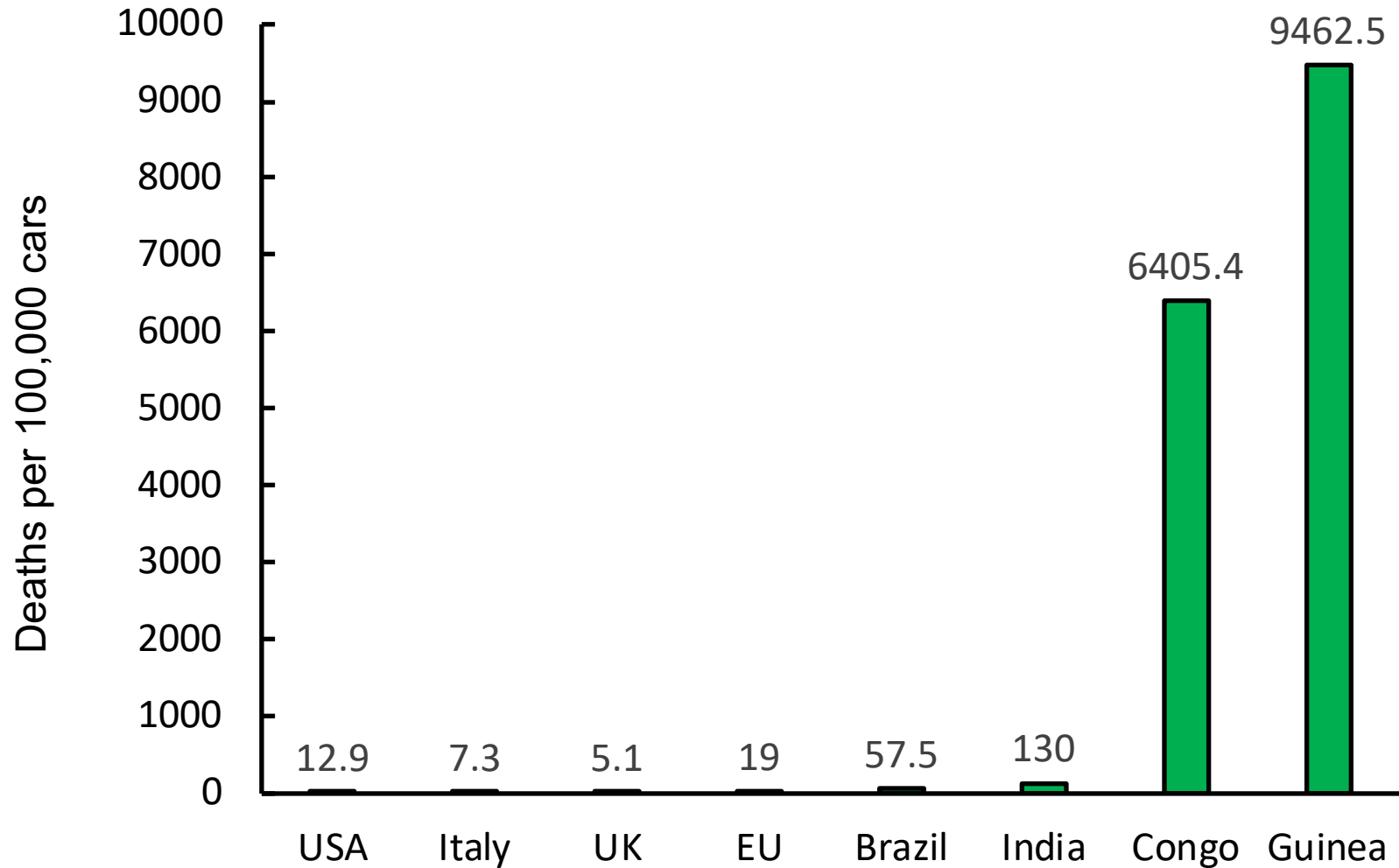
World Health Organization Data



World Health Organization Data

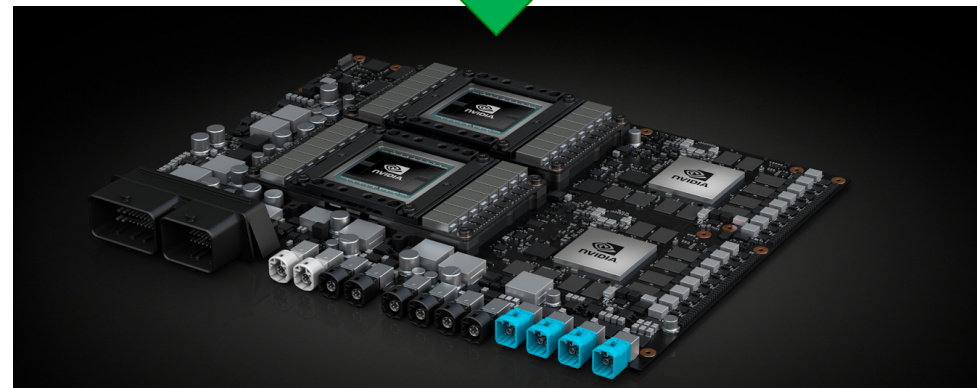
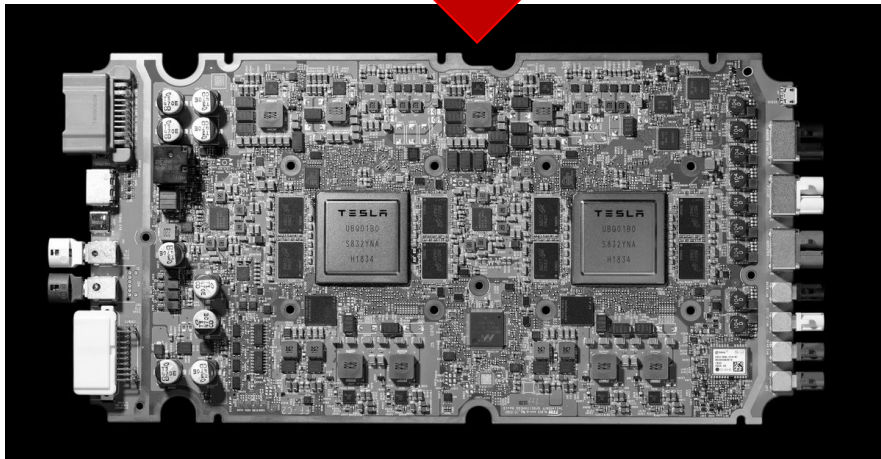
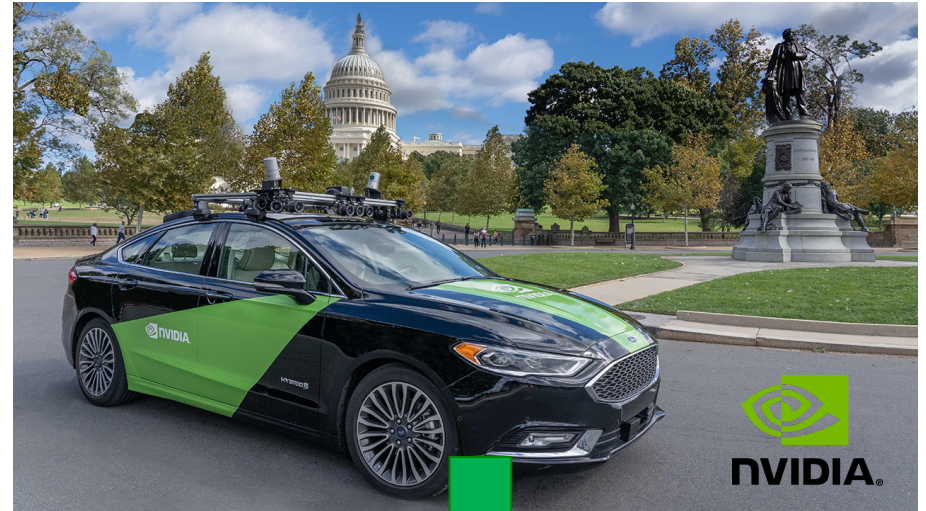


World Health Organization Data



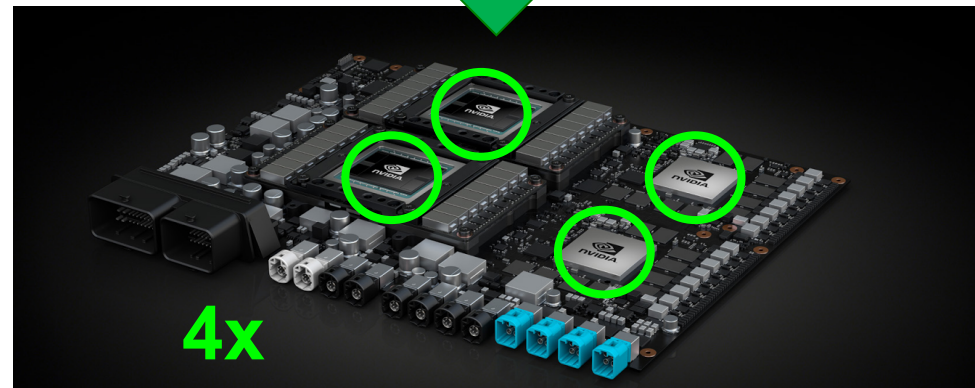
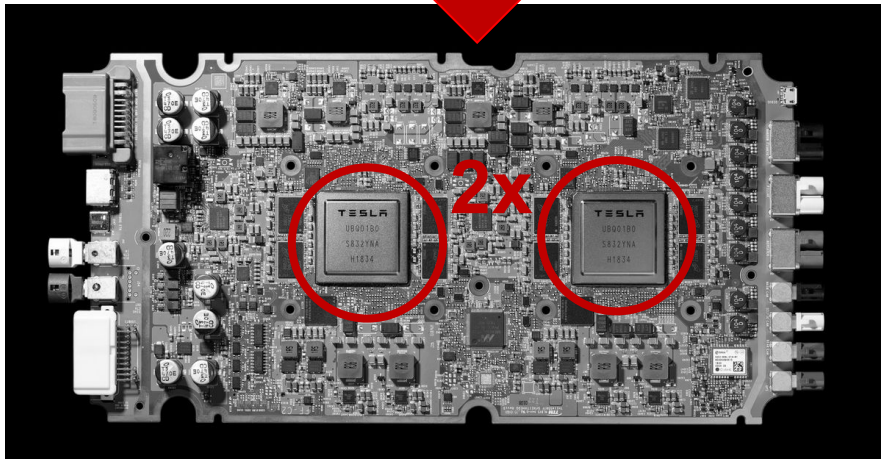
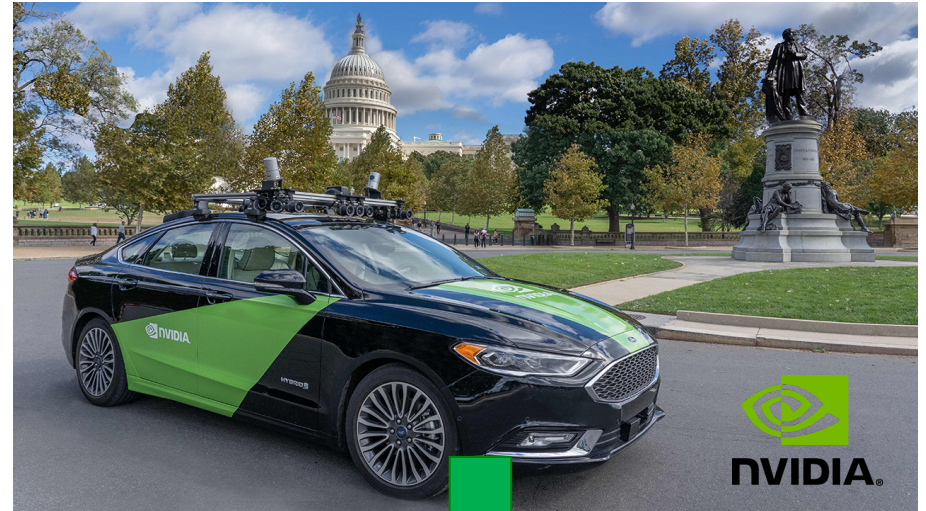
Self-Driven Cars

Naïve (expensive) solutions in today's self-driven cars



Self-Driven Cars

Naïve (expensive) solutions in today's self-driven cars

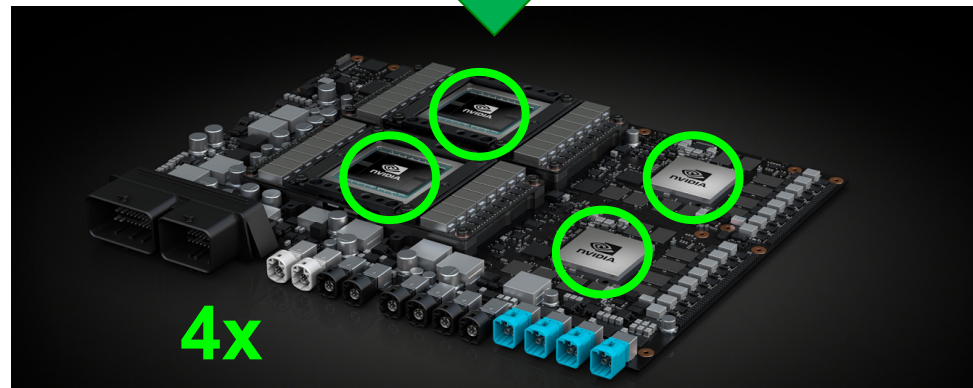
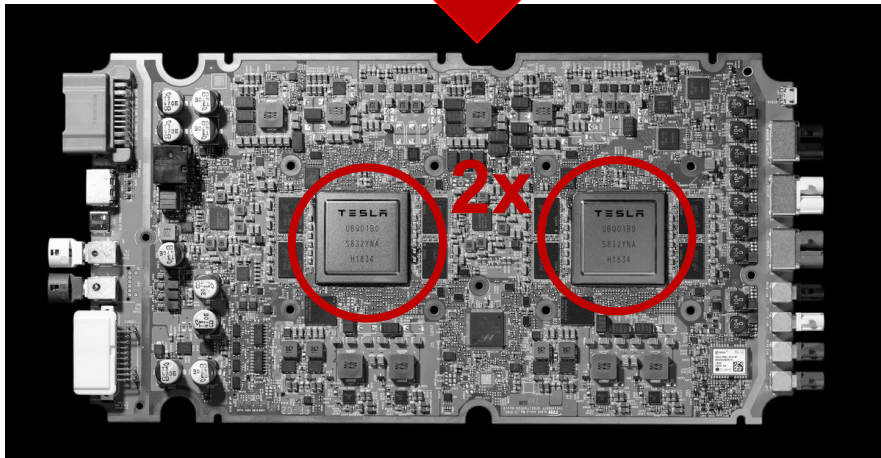


Self-Driven Cars

Naïve (expensive) solutions in today's self-driven cars

Replication is **very costly!**
And it might **not work always!**

We need to find **smarter ways** to detect neutron-induced errors.



- Why neutrons disturb computing devices
- Evaluating neutron-induced errors probabilities
- “Fun” facts about neutron-induced errors
- Some (interesting) results on self-driven cars
- **What's next?**

What's Next?

- Neutrons impact electronic devices executions, corrupting the output or inducing crashes/hangs
- It is very hard to detect neutrons-induced errors
- The effect of the neutron-induced error depends on the applications. Self driven cars require very high reliability.
- Accelerated beam tests are necessary to evaluate devices error rates and to understand the behaviors of corrupted applications.

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Steve Wender



Timothy Tsai
Siva Hari
Steve Keckler



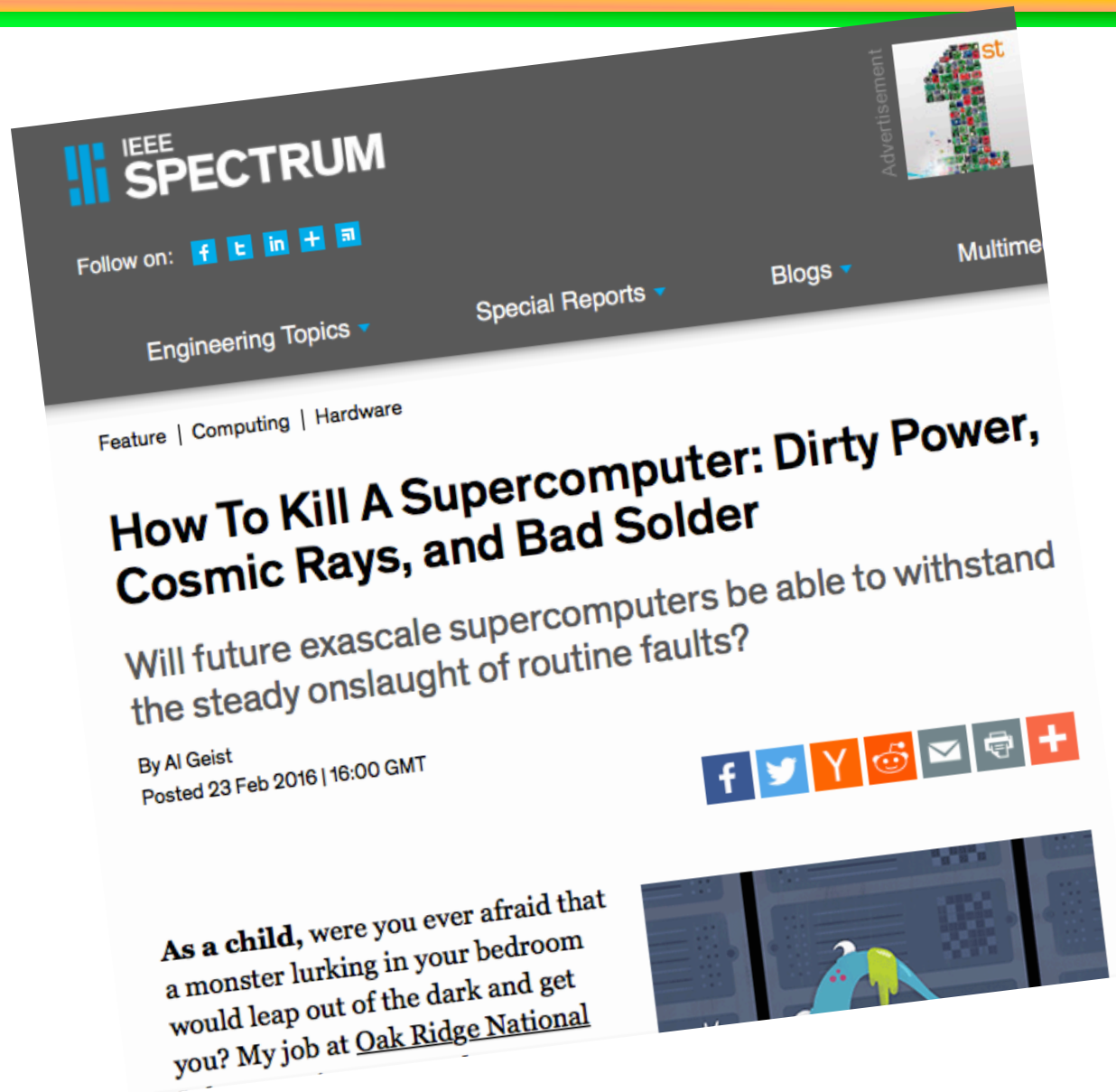
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Balaji Venu
Reiley Jeyapaul



Matteo Sonza Reorda
Luca Sterpone

Reliability importance



Reliability importance



Reliability importance

SARAH SCOLFE

AARIAN MARSHALL TRANSPORTATION 03.31.18 07:00 AM

THE UBER CRASH WON'T BE THE LAST SHOCKING SELF- DRIVING DEATH



Reliability importance



The reliability of electronic devices is a critical issue!

